THE CITY & SOUTH LONDON RAILWAY.

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CITY AND SOUTH LONDON RAILWAY;

WITH SOME

REMARKS UPON SUBAQUEOUS TUNNELLING BY SHIELD AND COMPRESSED AIR.

BY

JAMES HENRY GREATHEAD, M. Inst. C.E.

WITH AN ABSTRACT OF THE DISCUSSION UPON THE PAPER.

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SIR BENJAMIN BAKER, K.C.M.G., LL.D., F.R.S., President, in the Chair.

(*Paper No. 2873.*)

"The City and South London Railway; with some Remarks upon Subaqueous Tunnelling by Shield and Compressed Air."

By JAMES HENRY GREATHEAD, M. Inst. C.E.

PROBABLY the most general requirement of great cities is a good system of internal communication for passengers. This want has been urgent in London for many years; for although the transit facilities outside an area bounded by a line joining the termini of the great railway companies are, with exceptions, fairly good, within that area they are of the slowest and most inconvenient description. Even the suburban facilities are falling behind the requirements of the rapid development of traffic, for there are already large occupied areas, within half-a-dozen miles of the great centres of the east and west of London, which it is impossible to reach in a reasonable time, and with reasonable comfort. It would be interesting to trace the prodigious growth of traffic during the last twenty-five years within the Metropolitan area, brought about by the existing facilities for inter-communication, and the growing requirements of the population. Although this cannot be done now, the Table on the following page, prepared from official sources, will suffice to show that the traffic has increased out of all proportion to the growth of the population.

This statement does not deal with the suburban traffic of the railways entering London, nor with that of the North London Railway, where the facilities have remained practically stationary for a long period. And no account is taken of the development of the cab and private omnibus traffic, which has probably been not less rapid. About three-fourths of this traffic has been carried at a speed of between 5 miles and 6 miles an hour, and its growth

cannot compare with that of the elevated railways of New York where, upon one line alone, about 8 miles long, giving an average speed of about 12 miles an hour, the traffic grew in thirteen years from the opening of the railway in 1878 to over 83,000,000 in the year 1892-93. The passengers carried by the elevated railways and

TABLE SHOWING GROWTH OF TRAFFIC DURING YEARS 1864–1894.

—	Number of Passengers carried.			
	1864.	1874.	1884.	1894.
London General Omnibus Company . .	42,650,000	48,340,000	75,110,000	133,132,000
Metropolitan Railway	11,720,000	44,120,000	75,930,000	88,514,000
District Railway . .	..	20,770,000	38,520,000	42,097,000
Tramways	..	41,930,000	119,260,000	231,522,000
Road Car Company .	..	..	3,060,000	44,610,000
City and South London Railway . .	..	..	..	6,959,000
Totals . . .	54,370,000	155,160,000	311,880,000	546,834,000
Population . . .	2,940,000	3,420,000	4,010,000	4,349,000
Ratio of passengers to population . . .	18 to 1	45 to 1	78 to 1	126 to 1

tramways in New York amounted in 1889 to nearly 400,000,000, or to over 260 times the population of the city. There can be no doubt but that the traffic in London would, with better facilities, have grown more rapidly than it did. Even at the recent rate of increase, if facilities are given, there will before the end of the century be about 200,000,000 more passengers to be carried annually, than at present.

The great want is for facilities for the rapid transport of passengers in the central portions of the metropolis which are now served only by omnibuses, owing to the necessary exclusion of tramways from the congested thoroughfares. It may be stated generally that where the need of communication is most pressing the making of railways in the ordinary manner is most difficult and costly, and is attended with loss and inconvenience to the inhabitants. The ceaseless activity which makes the railways so desirable cannot bear the interference inseparable from their construction.

The question of the relief of street traffic in London has occupied the attention of engineers for half a century and more, and numerous proposals have been made for overhead and underground railways and subways to be worked by various means. In

1867 the late Mr. Peter Barlow, F.R.S., proposed a system of what he called "omnibus subways," consisting of iron tunnels 8 feet in diameter, in which single steel omnibuses, to seat twelve passengers each, were to be propelled by man-power aided by gravity, without stations (in the ordinary sense), the passengers paying in the omnibuses. The stopping-places were to be at one level, and to provide for the differences of the surface level in the more elevated districts, it was proposed to have "three series of subways at different levels, the carriages as well as the passengers being lifted in passing from one to the other." The Tower Subway, referred to later in the Paper, was designed to be worked in this manner. Pneumatic railways were proposed at one time, and a pneumatic tube for parcels between St. Martin's-le-Grand and Holborn was constructed and worked. Railways high in the air, over the tops of the buildings, were from time to time proposed, and schemes for ordinary underground lines in every direction were brought forward—being in several cases authorised by Parliament. It is, however, impossible now to refer more particularly to these indications of the ever-present and growing need for improved facilities. After the completion of the Metropolitan and District railways nothing was accomplished in the way of internal railway facilities in London until the railway forming the main subject of this Paper was constructed.

The Act of Parliament authorising the construction of the City of London and Southwark Subway between King William Street, City, and the Elephant and Castle, Newington, was passed after considerable opposition, in 1884, but it was not until 1886 that the Company, under the chairmanship of Mr. C. G. Mott, was in a position to begin the works, with Mr. Edmund Gabbutt as contractor. In 1887 another Act was obtained for the extension of the line to Stockwell, and a later Act sanctioned a further extension to Clapham Common, the name of the undertaking being changed to that which it now bears. By another Act, passed in 1893, an extension northwards through the City to Islington was authorised.

The first object in starting the works of the original line was to construct the two tunnels under the Thames, because there was great misgiving in the minds of many people as to this part of the work. It was freely predicted that the whole capital of the Company would be insufficient for this portion of the undertaking alone. A temporary stage and shaft having been constructed in the river, immediately behind the Old Swan Pier, near London Bridge, the first tunnel was commenced in October 1886. The second tunnel was started in March in the following year, and by

June, both tunnels were completed under the river. In July 1887 work was begun upon the site of the station at St. George's Church, Borough, but it was not until the end of the year that the sinking of the "Elephant and Castle" station shaft was begun; the shaft at the City station being started three months later, in March, 1888. About this time tunnelling was commenced at Kennington Park, on the Stockwell extension.

Before the end of the year 1888, Messrs. Sir W. G. Armstrong, Mitchell & Co., were at work on the hydraulic lifts and machinery for giving access to the stations; and in 1889 the contract for the electrical equipment was let to Messrs. Mather and Platt. The experimental running of the electric locomotives and two of the carriages, was commenced in February, 1890, on the City section, and continued from time to time until the completion of the works.

The inauguration by H.R.H. Prince of Wales on the 4th November, 1890, was followed on the 18th December by the opening to the public. In the first half year 174,000 train-miles were run, and 2,412,000 passengers were carried. In the year 1894, 458,000 train-miles were run and 6,900,000 passengers were carried.

Description of the Railway.

Starting under and at right angles to King William Street, near the Monument, at a depth of about 70 feet below the surface, the railway runs under Arthur Street West, and Swan Lane to the River Thames, under which it passes at a maximum depth of 73 feet below high water. The railway continues under Hibernia Wharf and Chambers on the south bank, and the southern approach to London Bridge and below the following streets: High Street, Borough, Blackman Street, Newington Causeway and Butts, Kennington Park Road and Clapham Road to Stockwell where, at the junction of the South Lambeth and Stockwell Roads, the line at present terminates. Except where it passes under the Thames and one property on its south bank, the railway is under the public thoroughfares throughout. The course of the railway is shown in Fig. 1, Plate 1, and it will be observed that two existing railways were passed under, viz. the South Eastern, and the London Chatham and Dover.

The section, Fig. 2, Plate 1, shows the main gradients of the two lines which are, excepting at the termini, carried in two separate tunnels. Fig. 3, Plate 1, illustrates the method adopted for driving the tunnels in loose water-bearing strata (see p. 28). In places it

will be observed that the lines are at different levels, as at Swan Lane, which was not wide enough to admit of the tunnels being placed side by side without encroaching upon private property, Fig. 4, Plate 1, and Fig. 7, Plate 2. At the termini the lines converge into one tunnel in order that the trains may pass from one line to the other. A longitudinal section is given, Fig. 5, Plate 1, of the terminal station at Stockwell, of which a plan is also shown in Fig. 27, Plate 3. The terminal station in the City, Fig. 6, Plate 2, has two platforms for "arrival" and "departure," and a single line of rails; at Stockwell there is a central platform with a line on each side of it, so that two trains may be in the station at one time, to provide for the examination of trains and adjustment of running times, &c. Cross-sections are also shown, Figs. 8, 9 and 10, Plate 2, of three of the intermediate stations. At two of them there is a difference of level of 9 feet 6 inches between the lines; in one case the line further away from the entrance-shafts is the higher, and in the other case the lower. The difference of levels was arranged in order that, with a station upon one side only of the street there should be a minimum number of stairs between the lower lift-landing and the two platforms. Access to and from one of the platforms, Fig. 9, Plate 2, is obtained without any stairs by passengers using the lifts, while the other platform is reached by a single flight of stairs, either up or down, but not both; in the other case, Fig. 10, there are no stairs. At the "Elephant and Castle" Station, Fig. 8, Plate 2, the lines are at one level to admit of a cross-over road and lay-by being introduced between the up- and down-lines, and at this station also access between the lifts and the platforms could be and has been obtained by inclines, and there are no stairs.

The Act prohibited the use of steam locomotives, and the original intention was to use the endless-cable system of haulage. There were to be two cables, one between the City and the "Elephant and Castle," the other between the "Elephant and Castle" and Stockwell, and it was intended in the first instance to drive the former at 10 miles per hour and the latter, the line being straighter and more level, at 12 miles per hour. For this reason the tunnels on the latter section were made somewhat larger than those on the first section, viz. 10 feet 6 inches in diameter instead of 10 feet 2 inches. Owing to the progress made in electric traction during the construction of the line, it was determined to adopt that motive power in preference to the endless cable, which will, however, receive a trial shortly on the Glasgow District Subway.

It was determined first to execute the upper tunnel southwards under the river, Fig. 4, Plate 1, and in October 1886 the shield for this tunnel was lowered into position to rest upon a platform in the shaft, and the tunnelling was commenced southwards in clay. The work at first proceeded at a very slow rate, not more than 23 feet being accomplished in two weeks. But, as the workmen became more experienced in the use of the novel machinery, and after improvements were made in the appliances, the speed was augmented, until it reached as much as 16 feet per day at a face, and 80 feet per week for many weeks together. This tunnel reached the south bank of the river in February 1887, and was then driven under Hibernia Wharf and Chambers and near to the southern abutment of London Bridge towards the Borough. The second tunnel was, in the same month, started from the temporary shaft at Old Swan Pier immediately underneath the first, but, taking a slightly different direction, it was brought to the same level as the first at the south bank of the river, which was reached in fourteen weeks from the start, and then carried parallel with it under Hibernia Chambers and the South Eastern Railway.

The upper tunnel was meanwhile driven northwards from the Old Swan shaft, and at about 60 yards from the river the clay was pierced and a large volume of water encountered. The face of the shield was at once closed and a bulkhead and air-lock were subsequently erected in the tunnel. After about 50 yards of the tunnel had been driven under compressed air, the shield again entered the solid clay, and, the joints of the tunnel having been caulked with iron cement, the air-pressure was relieved, and the remainder of the tunnel was driven to the terminus in King William Street under the normal air-pressure. It was observed that the air which escaped from the tunnel found its way out into the river over a considerable length, between Cannon Street and London Bridges; and the pressure of the air in the tunnel automatically adjusted itself to that due to the varying head of water in the river, between high- and low-water.

The upper and lower tunnels were then excavated simultaneously, the upper being about 100 yards in advance. These tunnels were carried round the curve under Arthur Street West, 140 feet in radius, without difficulty; and, one of them having been completed across King William Street to Arthur Street East, the 25-foot shaft was commenced within the building No. 46 King William Street. In order to reduce to a minimum the carting of spoil and materials in the City, a 4-foot square timbered shaft was

sunk within the site of the 25-foot shaft and connected by a small heading with the tunnel below. The whole of the material excavated from the shaft and station was sent down the tunnel to the river shaft, whence it was carried away in lighters.

On the completion of the iron tunnels under the river, land was acquired for the "Borough" and "Elephant and Castle" stations, and operations were commenced at these places by sinking the 25-foot lift shafts, to be used in the construction of the tunnels. When this had been accomplished at each place a heading was driven under the street at right-angles to the course of the railway. Four shields were then lowered and rolled into position for driving the two tunnels northwards and southwards. Meanwhile the company, having obtained an Act for the extension to Stockwell, had let the work to Messrs. Walter Scott & Co. in August 1887. These works were soon in progress at three points, viz., Kennington, the Oval and Stockwell, and the operations on both sections proceeded simultaneously until the City section was completed.

Temporary Shaft in the River.—For the sake of the ready disposal of the excavated material, and to avoid the delay generally attending the acquisition of property, it was determined to commence the tunnels in the river itself from a temporary shaft sunk into the bed, clear of the foreshore and wharves. Piles were driven into the gravel overlying the clay; and, a working stage having been formed 100 feet long by 35 feet wide, the iron rings of a 13-foot diameter shaft were bolted together and sunk, without pumping, through the gravel and into the clay by means of a grab. To maintain a uniform level between the water in the shaft and that of the river, which rose and fell with the tide about 19 feet, a valve was provided in the shaft lining below low-water level. In this way the material surrounding the shaft was not disturbed by the inflow and outflow of water during the sinking, and the valve was not closed until the shaft was well into the solid clay. The lower portion of the shaft was completed in brickwork in cement with four openings or "eyes" from which to start the two tunnels northwards and southwards, Fig. 4, Plate 1. The temporary shaft was sunk to a total depth of 82 feet below high water; and the lower 9 feet of the shaft were and are used as a sump for the collection of the drainage from the two tunnels, both northwards and southwards. The upper portion above the bed of the river was removed after the length immediately over the tunnels had been closed and made watertight with concrete, asphalt and puddle.

Non-Interference with Street-Traffic.—In 1864, when a joint committee of the two Houses of Parliament considered the large number of railway projects within the metropolis then brought forward, the committee reported against a number of the proposals on the ground that their authorization would involve inconvenience during construction. In applying for the Act for this railway there was much opposition to the granting of power to construct temporary shafts in the streets. It was not urged that the work could be done without them, but that as temporary shafts were necessary, the line should not be made. The power, however, was given, hedged round in some cases by conditions; but it was found after some experience in the new construction that it would not be necessary to sink any temporary shafts, and the power was not exercised. The cost of constructing, maintaining, and filling the temporary shafts was saved, but, on the other hand, the length and cost of underground haulage were greater. The temporary shaft in the river was of great use in constructing the tunnels and the station in the City. Through it were passed all the excavated materials, iron, bricks, &c., not only citywards, but also southwards for a distance of more than ½ mile. From the position this shaft occupied in the river, it offered no obstruction to the navigation, and as all the land-shafts were upon private property of the company there was no obstruction anywhere to traffic.

Separate Tunnels for Up- and Down-Lines.—The advantages of two tunnels instead of one as regards ventilation are dealt with later in the Paper. The other considerations which weighed in favour of separate tunnels may be summarised thus:—

1. They could be constructed where a single double-line tunnel could not be, as for instance, under Swan Lane, Upper Thames Street, Fig. 7, Plate 2. In this locality the value of property is very great, and it is impossible to estimate the saving effected by the adoption of two superposed tunnels here; the lane being little wider than a single-line tunnel.

2. The lines could be placed at different levels at the stations for convenience of access, as at three of the stations on the railway, Figs. 9 and 10, Plate 2.

3. Where junctions are intended or may be required at a future time, the placing of the lines at different levels enables a junction, without a level crossing, to be made without the cost of extended "fly-over lines."

4. A dip could be given to the lines, as carried out on this railway to some extent between the stations, for obtaining a higher speed or lower cost of working or both, maintaining the gradients

against the load, that is to say, approaching the stations, at such a moderate inclination that trains could always surmount them, while giving to the gradients with the load, that is to say, on leaving the stations, such a steepness as to secure rapid acceleration. The approaching gradients are 1 in 100 and the departing gradients 1 in 30. If both lines had been in one tunnel, the gradients with and against the loads would necessarily have been the same.

5. Where headway is important, as, for example, at crossings of sewers, or railways, or under a river-bed, the two tunnels give an advantage as compared with one.

6. Greater safety in construction is secured where the tunnel is of little more than one-fourth the cross-sectional area of a double-line tunnel.

7. The two tunnels are cheaper than one, and involve less carting and disposal of excavated material, a matter of importance in a great city not only to the company but possibly to the local authorities and to the public.

Borings.—Frequent borings, generally 3 inches in diameter, were made from the surface along the course of the railway sufficiently far in advance of the work to allow of arrangements being made to meet the conditions of strata thus ascertained. These borings disclose the interesting fact that the tunnels are throughout their whole length, except for about 50 yards at the City Station, subaqueous. Where they are not under the river, they are under or in water-bearing strata, having generally communication with the river as evidenced by the rise and fall of the water, to a greater or less extent, at intervals of time corresponding with the tidal movements in the river.

Shafts.—The lift shafts, of 25 feet internal diameter, were used for the purpose of constructing the tunnels. They are lined partly with cast-iron segments and partly with brickwork in cement. The iron portion, with a cutting-edge but no external projection, was sunk from the surface through the water-bearing strata and 3 feet or 4 feet into the clay. The tunnel segments were used as kentledge, for which purpose their shape rendered them very convenient. Some details of the cast-iron work are shown in Figs. 24 and 25, Plate 3. Below that level they were continued to the full depth in brickwork in cement, built in sections and in underpinned lengths of about 6 feet, with arched openings for access to both ends of the lifts. A circular passage round about half the circumference at the foot of the shaft was subsequently tunnelled.

By making the joints between the iron segments some time before they reached the water, perfect watertightness was secured. None of the segments were planed or turned, and no internal lining of concrete or brickwork was introduced; the flanges were found to be very convenient for attachment of the lift guides.

In constructing the 15-foot shafts for the stairs, the iron lining was carried the whole depth. The water-bearing strata were pierced in the same manner as in sinking the larger shafts. When the cutting-edge had penetrated 3 feet or 4 feet into the clay, the excavation was carried down as for underpinning in brickwork, but was not intentionally undercut beyond the outside diameter of the iron above. Iron segments, similar to those used in the upper part, were then introduced and bolted to the latter. Through holes in the castings, provided for the purpose, blue lias grouting was then forced by the grouting apparatus, to be described, into the small space behind the castings. This system of construction was found to be very convenient and inexpensive, as avoiding the handling of kentledge and other troubles connected with forcing cylinders down to considerable depths. It was much more expeditious than the underpinning in brickwork, with its accompanying undercutting and greater excavation. In this manner iron-lined shafts of uniform diameter can be carried down to any depth, and in close proximity to buildings. The 25-foot shaft for the City station was sunk within a heavy building, the walls of which were only just far enough apart to contain the shaft, which was carried to a depth of 75 feet through made ground, gravel and clay, partly with iron-lining and partly with brickwork, without injury to the building.

Gradients and Curves.—As has been already stated, it was originally intended to work the traffic by the endless cable system. The gradients and curves adopted were, consequently, steeper and sharper than would have been contemplated for a line to be worked by locomotives. The curves, however, could not have been reduced without taking an altogether different route, involving risk of serious opposition or heavy expense for right of way under buildings, or both.

Dip or Depression between Stations.—On a line with frequent stations and where all trains stop at every station, the provision of a certain dip or depression between the stations, depending upon the maximum speed allowable, is of great advantage to the obtaining of a good average speed and economy of power. Taking the case of a line having stations ½ mile apart, upon which a maximum speed of 25 miles per hour, having regard to

curves, &c., is permissible, to attain this speed as much power must be expended as would lift the train through a height of 21 feet. If the average resistance to movement be taken at 10 lbs. per ton, this would require for the ½ mile between the stations, as much power as would lift the train $\left(2,620 \times \frac{10}{2240}\right)$, or nearly 12 feet. The two together $(21 + 12)$ would require power represented by that necessary to lift the train vertically 33 feet. Thus about two-thirds of the propelling power would be expended in getting up speed to be nearly all dissipated by the brakes in stopping. By arranging a dip of 21 feet between the stations, the same or a greater average speed could be maintained with about one-third to one-half of the power. This principle, which has often been proposed, but which cannot be fully realised in practice, has been carried out where practicable on the City and South London Railway, to the extent of accelerating up to the cable speed originally intended, viz., 12 miles per hour; it is found to be of great advantage in working the line. It would give an additional advantage in working by cable, by reducing the destructive slip between the cable and the gripper while accelerating, thus greatly prolonging the life of the cable.

Station Tunnels.—At each of the stations, for the length of the platforms and at the termini for a greater length, enlarged tunnels were constructed in brickwork. At the termini these tunnels are 26 feet wide and 20 feet high from invert to crown, with walls and arch 3 feet thick. In the City the whole of the bricks used were Staffordshire brindles. At Stockwell the face for 9 inches was brindles, the rest being good stocks. At the intermediate stations there are two tunnels, 20 feet wide and 16 feet high from invert to crown. In the cases where the two tunnels are at different levels, the lower tunnel was constructed in advance of the other, one wall of the upper tunnel being built upon one of the walls of the lower. At the "Elephant and Castle" Station the two 20-foot tunnels were built side by side, Fig. 8, Plate 2, at the same level, in order that a cross-over road, long enough to serve as a lay-by siding for two trains, could be driven between the "up" and "down" lines. Great care was exercised in carrying out the brick tunnels. Heavy timbering was used, and the lengths were short. In the earlier work 5-foot lengths were used, but experience proved that a 9-foot length was better, as enabling the forward face of the excavation and supports for the bars to be in more solid and undisturbed material. Notwithstanding all the precautions taken, however, some slight disturbance of the material

overhead generally took place, but in the later work of Messrs. Walter Scott and Co. this was reduced to a comparatively small amount. All the brick tunnels are in London clay, except a short length at Kennington, where the invert is in wet sand, and where it has not been found practicable to completely exclude the water.

Alignment.—In the absence of intermediate points between the shafts at the respective stations for testing the accuracy of the work, great care was necessary in the alignment. Some exceedingly good results were obtained, for instance, the lines were carried from the 25-foot shaft at Kennington Station, 30 yards off the line of tunnel, to the "Elephant and Castle" Station, a distance of 900 yards, traversing a number of curves, with a total divergence of only $\frac{5}{8}$ inch; and again between the Oval and Kennington with a smaller divergence. These examples are interesting as indicating what can be done with good instruments in careful and competent hands; and credit is due to Mr. Basil Mott and Mr. David Hay for the good results obtained.

Lifts.—As an elementary principle it would seem to be better to bring all stations quite near to the surface, and that, no doubt, was a leading principle when the Metropolitan Underground Railways were laid out; but even on those lines the platforms are often a considerable depth below the street levels, and the ascent and descent of fifty or sixty steps has to be encountered. In 1884, when the proposal was made to raise and lower the passengers by lifts on the City and South London Railway the Mersey Railway lifts had not been constructed, and it was contended by opponents of the project that the lift formed a serious objection. Even since the opening and working of both of these railways, it has been urged against the extensions of the system, both in this country and abroad, that the necessity of employing lifts outweighs all other advantages of the deep-tunnel system. A cursory examination, however, should suffice to show that these contentions are ill-founded. By the use of lifts in London, the construction of the line underneath all sewers and pipes and in the London clay is rendered practicable. The cost of constructing railways near the surface, even if the obstruction of traffic could be permitted, would generally be much greater having regard to the necessity of underpinning buildings, diverting and reconstructing sewers, pipes, &c., and, in narrow thoroughfares, of interference with cellars of houses. The deep tunnels insure against injurious vibration and noise.

The cost of working the lifts is small compared with their convenience, and with the extra cost of and other objections to the

construction of railways near the surface, including in many cases the cost of dual establishments on opposite sides of the street, as at Baker Street and Gower Street on the Metropolitan Railway. The public do not object to lifts, as has been assumed by opponents, but on the contrary would hail with satisfaction their installation at many of the stations on the Metropolitan and other railways in London.

The stations alone might be placed near the surface with dips between them; but this would entail considerable interference with streets and sewers, &c., and the tunnels would be more expensive by reason of their having to be driven for considerable lengths through water-bearing strata under compressed air instead of wholly in the London clay. The railway projected in 1885 between King's Cross and Waterloo embodying this principle was threatened with such serious opposition by the Metropolitan Board of Works and the other local authorities that it was withdrawn.

It was decided on the City and South London Railway to adopt suspended lifts in preference to direct-acting lifts, as being lighter and, for large lifts, more rapid, and, owing to the absence of deep wells, as having every part open to inspection and accessible at all times. It may be interesting to note that this application of the suspended form is a return by Messrs. Sir W. G. Armstrong, Mitchell and Co. to the original lifts of Lord Armstrong, introduced nearly forty years ago.[1] The Author does not contend that suspended lifts would in all cases be the best form; on the contrary he is of opinion that in many cases direct-acting lifts would have preponderating advantages.

There are two lifts in the 25-foot shaft at each station of depths varying between 43 feet at Stockwell and 67 feet at King William Street. The cages are approximately semicircular in plan, and each accommodates between fifty and sixty passengers, who enter and leave at either end. The lifts are worked quite independently of one another. The details of this work are shown in Figs. 24 and 25, Plate 3. The whole of the lifts are worked by pumping engines placed in the engine-room at Stockwell, where the pressure in the main is about 1,200 lbs. per square inch. The pressure and return-water pipes are carried upon brackets placed in the tunnels, Figs. 14 and 15, Plate 2. In addition to the main accumulator at Stockwell, another is placed in the stair-shaft at the "Elephant and Castle" Station for the purpose of equalizing the pressure.

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[1] Minutes of Proceedings Inst. C.E., vol. ix. p. 376.

There are three pairs of pumping engines, so arranged that each can be worked independently of, or jointly with, either of or both the others, and controlled automatically by the accumulator in the usual way.

Permanent Way.—It was thought to be very desirable to avoid the introduction of ballast on this line with a view to the comfort of travellers, having regard to the strong air currents set up by the trains, and to the durability of rolling stock, especially of the electric locomotives, and of the way itself. The rails, weighing 60 lbs. per yard, are placed upon cross sleepers resting directly upon the cast-iron segments of the tunnel, Figs. 14 and 15, Plate 3. The rails, it will be observed, are single-headed and are set some distance from the ends of the sleepers. This permanent way, though subject to the disadvantage of increasing the resonance in the tunnel, gives remarkably good results as regards repairs and maintenance.

Ventilation.—One object in placing the up- and down-lines in separate tunnels was to secure ventilation by the action of the trains. Where trains pass to and fro in the same tunnel their action in renewing the air in the tunnel is comparatively slight, unless frequent passages of short length between the outer air and the tunnel be provided. Any considerable transporting action of the train extends only for a short distance in front of and behind the train, hence the great importance of what have been called the "blow-holes" on the Metropolitan Railways. Where, on the other hand, separate tunnels are provided without an escape for the air, except through the stations and their passages, the draft or blast of air on the approach and departure of a train having a cross-section large in proportion to that of the tunnel, becomes inconvenient and a source of discomfort, while the resistance offered by the air to the movement of the train is considerable. The first objection, but not the last, can be obviated by providing openings to the air of sufficient area at each end of the station platforms. Both can be avoided by placing connecting passages between the tunnels, capable of being enlarged or reduced, for regulating the through draft. This expedient was adopted on the City and South London Railway, and with quite satisfactory results, because in the absence of steam locomotives it is not necessary to renew a large quantity of air on the passage of each train. Sufficient provision must in such cases be made at each station for the successive outflow and inflow of air.

The deep tunnels of the railway give considerable climatic advantages. From observations taken on a hot day in summer and

a cold day in winter, with surface temperatures of 85° F. and 22° F. respectively, the temperatures in the small tunnels were about 60° and 59°, on the station platforms 59° and 50°, and in the first coach of a train 62° and 57° respectively. In foggy weather the atmosphere below is comparatively clear, never exceeding a slight haze, even during dense fog on the surface.

Drainage.—For the permanent drainage of the tunnels, small injector-hydrants were placed in the invert at every depression, and connected to the hydraulic main supplying the lifts and to a 2-inch pipe carried along the tunnel to and up the nearest shaft. These injectors, Fig. 15, Plate 2, have been found most satisfactory in working. They cannot get out of order, and require very little attention. All that is necessary, when water is found to have accumulated, is to open a small valve for a few minutes, and the water is discharged into the nearest sewer.

Depôt.—The connection of the main line with the depôt at Stockwell is by means of an inclined siding, having a gradient of 1 in 3½, Fig. 5, Plate 1, and Fig. 27, Plate 3, up which the trains are hauled by wire rope and a stationary engine. In addition to the plant required for generating the electric and hydraulic power and for compressed air for the brakes, Fig. 28, Plate 3, there is a repairing-shop, a carriage-shed, pumps for water-supply, in addition to that of the Water Company, tanks, stores, &c. Since the opening of the railway, additional sidings have been constructed underground at Stockwell for working the increased train service.

Signals.—The signals, by Messrs. Dutton & Company, are of the usual railway type, modified to meet the special conditions of space. The absolute-block system is employed. Since the opening of the railway intermediate signal-stations have, with the sanction of the Board of Trade, been introduced on some of the longer sections, from which electric signals are given, by the passage of the train, to the station in the rear, enabling the next train to be started without waiting for the train ahead to reach the cabin in advance.

Lighting.—The trains are lighted by electric glow-lamps, but hitherto with not very satisfactory results. Experiments have been tried with accumulators for automatically regulating the pressure. These were, however, found to be unsatisfactory. The lighting by accumulators, charged from the main supply, would be possible, and was originally proposed by Messrs. Mather & Platt, but the necessary cost, weight and space led the directors to postpone their adoption pending the trial of other alternatives, and in the expectation that an efficient regulator would be forthcoming.

There is reason to hope that this desideratum is likely to be attainable in a short time. It was originally intended to light the stations from the main electric current, through accumulators, but this was abandoned on account of the considerable cost and trouble in working, and gas fittings were introduced. As affording a light independent of the running of the generating plant and always available, gas has decided advantages, but electric glow-lamps were soon substituted for it at all the stations, without any distressing variations of light, notwithstanding the absence of accumulators. The gas is now retained for use at such times (e.g. for cleaning the stations at night) as the generating plant is not at work.

Working.—In Table I of the Appendix are given the results of the four complete years' working of the railway since its opening. It will be observed that during that period the train-mileage has increased from 174,435 in the first half year to 230,604 in the last, but the total locomotive expenses have been reduced by some 12 per cent. in the latter. In other words, the locomotive expenses per train-mile have been reduced from 9*d.* to 5·9*d.* In the Paper[1] of Dr. Edward Hopkinson, and the discussion upon it, the electrical equipment and working of the railway have been already described and discussed. The electric locomotives of Messrs. Siemens, Brothers & Co. were referred to, but were not illustrated. The Author has, therefore, included two views of these locomotives, Figs. 22 and 23, and the train is shown in elevation in Fig. 26, Plate III. Up to December 31st, 1894, one of these locomotives had run nearly 76,000 miles. There had been no failures in the armatures, the repairs had been practically nothing, and the wire-gauze brushes had run for eighteen months without changing.

The contract for the first section of the railway was undertaken by Mr. Edmund Gabbutt, of Liverpool, who was unfortunately, through ill-health, prevented from completing it. Messrs. Walter Scott & Co., who carried out the extension to Stockwell and the completion of the City section, were represented on the works by Mr. William Sewell. Mr. Basil Mott, M. Inst. C.E., was the Resident Engineer on the extension, and, after the retirement from the City section of Mr. W. S. McCleary through ill-health, on the whole line. The Author, as Chief Engineer, was fortunate in being able to confer in emergencies with Sir John Fowler and Sir Benjamin Baker, the Consulting Engineers.

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[1] Minutes of Proceedings Inst. C.E., vol. cxii. p. 209.

TUNNELLING.

Historical.—As long ago as 1818, Sir Isambard Brunel took out a patent for "forming tunnels or drifts underground," the main principle of which was the forming of excavations suitable to tunnels of large dimensions "by an operation nearly similar to that of forming a small drift." The body or shell of the tunnel, he stated, might be made of brickwork or masonry, but he preferred to make it of cast-iron, and to line it afterwards with brickwork or masonry. In his patent specification, two modes of carrying out his system are described and shown, one by means of a number of small cells with friction rollers between them, each forced forward independently by any suitable mechanical aid, but preferably by hydraulic pressure. This method he subsequently employed, without the hydraulic presses, in the construction of the Thames Tunnel. In the other method, which he called a teredo, from its "analogy to the Teredo Navalis," he proposed to work spirally upon a small face of excavation nearly at right angles to the main face of the tunnel. It has never been used, and it would appear to be not quite practicable. The drawings show cylindrical tunnels of cast-iron combined with brickwork or masonry, but in the Thames Tunnel, commenced seven years later, Brunel adopted a rectangular section, probably as being more suitable for his form of shield; though Mr. Henry Law, in his account of the Thames Tunnel,[1] states that "the strata being horizontal and from their proximity to the river, subjected to constantly varying pressure, it was considered that a circular structure would have been exposed to very irregular strains." A circular section would certainly have been impossible of achievement with the form of shield actually employed by Brunel. With the abandonment of the circular section, the idea of using cast-iron for the lining of the tunnel became impracticable.

Though a great engineering triumph with the appliances available at the time of its construction, and a lasting testimony to the genius and spirit of Brunel, the mode of construction of the Thames Tunnel has not been attempted elsewhere; and there can be no doubt that for nearly half a century, that work served as a warning to engineers and capitalists not to embark in any undertaking of a similar character, and no other subaqueous tunnel was constructed. Indeed, so disastrous was that early experience that

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[1] "A Memoir of the Thames Tunnel," by Henry Law. Weale's Quarterly Papers on Engineering, 1845, vol. iii., and 1846, vol. v.

in 1868, when, an Act having been obtained for the construction of the subway under the Thames at the Tower, it was desired to let the work, no regular contractor could be found to undertake it. The Thames Tunnel was commenced in 1825 and was finished in 1842.

Tower Subway.—So far as the Author is aware, no other work of the kind was embarked upon until the little tunnel at the Tower, designed by the late Mr. Peter Barlow, F.R.S., was commenced in 1869. In the construction of this cast-iron tunnel, a cylindrical shield was used, which was forced forward as a whole by six screws worked by men inside the shield. The tunnel lining, of 6 feet 7 inches clear internal diameter, is composed of rings 18 inches long, each consisting of three segments and a key-piece, the metal being $\frac{7}{8}$ inch thick and the flanges $2\frac{1}{8}$ inches deep. The shield consisted of a cylinder of a single thickness, $\frac{1}{2}$ inch, of iron plates, made slightly tapered, the larger diameter being at the front end, to reduce the skin-friction of the clay on the outside. At the front end was a cast-iron ring with rounded edge forward, to which was bolted a diaphragm of wrought-iron plates, having a rectangular opening in the middle extending to within a few inches of the top, for the passage of workmen and materials. In rear of the face were fixed the six screws, each $2\frac{1}{2}$ inches in diameter, abutting against the forward end of the completed tunnel by which the shield was propelled. The tunnel is 1,350 feet long and in clay throughout, and with the shafts was constructed within the year 1869; the maximum speed reached being 9 feet per day of twenty-four hours divided into three eight-hour shifts. The shafts, 10 feet in diameter, are respectively about 50 feet and 60 feet deep, and the minimum cover over the tunnel under the river is 22 feet of clay. The shafts and tunnel were carried out by the Author for the company at a cost of about £10,000. Steam-lifts were subsequently placed in the shafts, and a small carriage, holding twelve persons, and of 2 feet 6 inches gauge was hauled to and fro through the tunnel by a wire rope and a 4-HP. steam engine in each shaft. The number of passengers that could be carried in this manner being too limited to pay working expenses, the machinery was soon discarded, and spiral stairs and a footway substituted, to enable foot passengers to use the subway.

Following the Tower Subway, a short length of experimental tunnel, 8 feet in diameter, was, in 1870, constructed in New York for the "Broadway Pneumatic Railway," and another similar short tunnel was afterwards built in Cincinnati. These tunnels

were not subaqueous, but shields of boiler plate similar to the Tower Subway shield, propelled by small hydraulic presses, were used. A short length of the Cleveland Lake Tunnel was subsequently constructed with a shield 6½ feet in diameter and 6 feet in length, composed of heavy boiler plates. It was propelled at first by means of screws, and afterwards by hydraulic presses. The tunnel lining was of masonry, and was inserted in 16-inch lengths. After 140 feet had been constructed in this way the shield was discarded, it was found impossible to prevent the cracking of the brickwork after each advance of the shield. In the New York and Cincinnati tunnels no attempt appears to have been made to close up the cavities left outside the lining upon the advance of the shield. Tunnelling by shield then fell into disuse in America, so that when in 1872 Mr. E. S. Chesbrough was preparing plans for the proposed tunnel at Detroit, he, after consideration, rejected the shield as unsuitable, and proceeded to construct the tunnel in brickwork in the ordinary way. The Detroit Tunnel was commenced in 1872 and was abandoned in the following year.

Several projects were, however, started in this country for constructing tunnels under rivers by means of shields and by other methods, such as cofferdams and caissons. Acts of Parliament were obtained in some cases, and in others refused; but nothing was actually accomplished until 1886, when the City and South London Railway tunnels were commenced. In one case, however, that of the North and South Woolwich Subway, a contract was let in 1876, and a shield with air-locks, hydraulic segment-lifting apparatus, and other machinery, and a large quantity of the cast-iron segments, were actually constructed to the Author's designs for driving through the sand and gravel forming the bed of the River Thames. The contractors however, owing to difficulties elsewhere, abandoned their contract. The late Mr. T. A. Walker, who did not believe in the shield method, expressed his willingness to carry out the work in his own way, which was to drive the tunnel through the chalk underlying the gravel. In the absence of financial strength, Mr. Walker's offer was accepted by the directors, and he was allowed to proceed with the work; but, having sunk a shaft into the chalk he found it impossible to proceed far with the tunnel, even though compressed air, without a shield, was tried, and the undertaking was subsequently abandoned.

In constructing the City and South London Railway tunnels through loose water-bearing strata, compressed air was in 1887 used in combination with shields.

Lord Cochrane, in 1830, took out a patent for "apparatus for excavating, sinking, and mining," being, to quote his specification, "an apparatus for compressing atmospheric air (into and retaining the air so compressed) within the interior capacity of subterraneous excavations . . . in order that the additional elasticity given to and maintained in the included air by aid of my apparatus . . . may counteract the tendency of superincumbent water to flow by gravitation into such excavations . . . and which apparatus at the same time is adapted to allow workmen to carry out their ordinary operations of excavating, sinking, and mining . . . within the space which is filled with compressed air, and also allow workmen ready passage to and from the space into the open air. . ." In his specification Lord Cochrane describes his apparatus as being an air-lock or locks, a water-column shaft and chain-dredge for materials, to be applied for sinking shafts or driving tunnels. The patent was taken out at the time that the Thames Tunnel was under construction, and the drawing shows a shaft and tunnel, the latter in clay, with air-locks in the tunnel, and an open end under the river. The patent has often been referred to as providing perfectly for the sinking of shafts through loose water-bearing strata, but it makes no provision for tunnelling through such materials beyond the air-lock; and indeed Lord Cochrane does not appear to have contemplated the use of compressed air in tunnels, except in materials impervious, or nearly impervious, to air and water, such as soft clay.

Compressed air was not used in the Thames Tunnel, nor, so far as the Author is aware, in any tunnel for many years. It was used without a shield in the first portion of the Hudson Tunnel, commenced in 1879, where the work was in almost impervious and fairly solid material; and also in a 4-foot 10-inch by 3-foot 10-inch and almost rectangular tunnel composed of cast-iron plates at Antwerp in very fine silty sand in 1879. The Hudson Tunnel was, in 1889, proceeded with under the advice of Sir John Fowler, Sir Benjamin Baker, and the Author, with a shield in combination with compressed air and cast-iron lining.

The first shield of the eighteen used on the City and South London Railway was almost identical in its design and construction with that shown in Figs. 11, 12 and 13, Plate 2, which represent a shield for the 10-foot 6-inch tunnels constructed between the "Elephant and Castle" and Stockwell. It consists of a cylinder 5 feet 11 inches long, of steel plates in two thicknesses of $\frac{1}{2}$ inch each riveted together to break joint with rivets countersunk on both sides. This cylinder was bolted to a strong

ring of cast-iron at the front end, and to this ring were bolted the plates and channel-bars forming the face, and the adjustable steel cutters. The latter were so attached that they could be adjusted to cut out the excavation to the same diameter as, or wider than, the steel cylinder following them; the latter provision being necessary for passing round curves in any direction either horizontal or vertical. In the face was provided a rectangular opening with iron doors upon rollers for sudden closing. It was, however, found in practice almost impossible to maintain these doors in working order, so they were subsequently removed and reliance was placed on timbers cut and kept ready for dropping into the channels placed for the purpose at the sides of the doorway. These were always used when work was suspended at a face, or when wet material was encountered pending the provision of appliances for dealing with such material. The inside of the cylinder in rear of the face was lined with massive cast-iron segments; and to these were bolted, as shown in Fig. 11, Plate 2, six hydraulic presses of $6\frac{1}{2}$ inches diameter. The presses were connected with two hand-pumps, for forcing the shield forward. The same pumps served also to run the rams back into the presses. To the projecting ends of the rams were attached long shoes for carrying the pressure on to the solid part of the cast-iron tunnel-lining without bringing any bending strains upon the rams, or undue pressure on the tunnel-flanges. The rear end of the shield, for a length of 2 feet 8 inches, consisted only of the steel cylinder; and within this the cast-iron segments forming the tunnel-lining were put together.

The tunnels on the first or City section are 10 feet 2 inches in diameter, and were composed of rings 1 foot 7 inches long, each ring consisting of six segments and a key-piece, Fig. 14, Plate 2. Southwards of the "Elephant and Castle," they are 10 feet 6 inches clear diameter, Fig. 15, Plate 2, in rings, 1 foot 8 inches long. The flanges of the tunnel are $3\frac{1}{2}$ inches deep and $1\frac{3}{16}$ inch thick, and the plates are nearly 1 inch thick on the City section; on the Extension the flanges are $3\frac{5}{8}$ inches deep and plates $\frac{7}{8}$ inch to $\frac{15}{16}$ inch thick. All holes were cast in the plates and flanges, and in no case was there any tooling of any kind upon the plates. They were cast from soft grey pig and dipped into a composition of pitch and tar while hot, which formed a good tenacious glazed coating upon them when cold.

The joints are shown in Figs. 16, Plate 2, and were found to be satisfactory. In the horizontal joints were placed, at the time of erection, soft-pine packings $\frac{1}{4}$ inch thick; and in the

vertical joints a rope of tarred hemp between the bolts and the "chipping edge." Subsequently the whole of the joints were packed or pointed with Medina cement. Where, however, the tunnels were driven through water-bearing strata, iron cement was caulked into the joints in place of the Medina filling, and with excellent results, for the tunnels in these positions are absolutely watertight. These caulked joints were made before the compressed air was taken off.

The shields were at first not made to do any of the excavation beyond the shearing off by the adjustable cutters of a thin slice of material round the circumference; but subsequently in driving through clay, the Author introduced a series of wedges or piles in front of the face. These were fixed in position against the front of the shield, and were made to enter the solid clay about 2 feet in advance of the cutting-edge by the hydraulic pressure driving the shield. The effect was to expedite the work and reduce its cost materially, the speed being practically doubled. The wedges were free to pass by the nodules of septaria, common in the London clay, without unduly straining the shield or presses. The timbers of the small heading, driven about 6 feet in advance of the shield, were, for a length corresponding to the advance of the shield, previously slackened to allow movement of the material inside the circle of wedges to take place towards the heading.

In the second half of 1888, 2¼ miles of the tunnels were driven, or an average of nearly 2,000 feet per month, or about 80 feet per day, at an average of six working faces. Frequently 100 feet per day were accomplished; and for long periods the tunnels in clay were carried forward 13 feet 6 inches at each face per day of twenty-four hours, divided into two shifts. It is worthy of remark that the men, who were miners and labourers from railways, sewers and similar works, showed remarkable readiness in adapting themselves to work so different from any to which they had been accustomed. Starting with a conviction that the new system was inferior to that to which they had been accustomed, and not hesitating to express their opinions, they soon came to see that the innovation had merits of its own, and eventually that it was superior to the old method. Once satisfied on this score they threw themselves into the work; and men whose lives had hitherto been spent in filling and running "muck," were to be found bending their energies to the working and guiding of the shields, erecting the iron, performing the grouting operations, and making the joints, with method and celerity. During the

whole progress of the works there was no fatal accident, speaking well for the forethought of the contractors and the carefulness of the men.

The shield should be very strong at its front end; and, unless in fluid or semi-fluid material, the tail end need not be very stiff. In all cases where the diaphragm forming the face has been placed well forward, and as near as possible to the cutting-edge, which has been made very stiff, no trouble has arisen. Any change of shape, however slight, at the cutting-edge must, as the shield progresses, tend to increase, and will inevitably lead to trouble. By increasing the strength at the front end, and reducing the shell or cylindrical plates of the tail-end to the minimum, consistent with safety, the annular space left by the advance of the shield round the outside of the tunnel-lining is reduced, and the quantity of grouting correspondingly diminished. This shell has been generally made in two or more thicknesses of steel plates, with rivets countersunk on both sides, thus giving a smooth surface both inside and out, without projecting cover-plates.

The doorway in the face of the shield should be placed as low as possible, in order that where the use of compressed air becomes necessary the portion of the face of the shield above the opening may form a safety-screen in the event of a sudden inflow of water, accompanied or not by material, from the outside. The water could not of course rise above the lower edge of this screen so long as the pressure of the air is maintained. The advantage of a screen in this position is that it is always at the front. The joint between the shield and the tunnel is always good enough to prevent great escape of air, and can by proper grouting be kept almost air-tight, even while the shield is being moved.

Segment-lifting.—The Author designed in 1873 for the Woolwich Subway a hydraulic segment-lifting apparatus which was made and on trial found to work admirably. The segments of the South London tunnels, however, weigh only 4½ cwt. each; and it was found that six men could easily and quickly place the six segments in their respective positions, using for the upper two and for the key-piece a light temporary stage, necessary in any event for bolting together the rings and segments. Small pulley-blocks were found useful for slinging the lower side segments, but beyond these no other mechanical appliances were employed. The objections to the employment of any lifting appliance in a small tunnel are that it interferes with other operations, it does not save time, and is somewhat costly to make and maintain. In

large tunnels, however, some such apparatus is essential, the segments being too heavy to handle and having to be lifted considerable heights.

Hydraulic Presses in the Shield.—The hydraulic presses in the shields used in the City and South London Railway were supplied with water from two cisterns placed inside the shield by hand-pumps one on each side of the platform in the shield, Fig. 11, Plate 2. These hand-pumps generally forced the shield forward in about ten minutes, overcoming the skin friction and the resistance due to wedging and cutting the clay in the face. The pressure varied between 500 lbs. and 1,800 lbs. per square inch, depending upon the number of presses in use, the projection of the cutters and whether the tunnel was being driven in a straight line or on a curve. A reversing valve enabled the rams to be driven back by the same pumps either singly, in groups, or all together.

In the case of large shields having a great number of presses, and requiring a considerable volume of high-pressure water, or where the pressure required to advance the shield is very great, it is expedient to set up a pumping-plant on the surface for the propulsion of the shield. This involves the fixing of high-pressure pipes between the surface and each shield with sliding or flexible connections at the shield. To avoid this, electric motors placed in the shield may be employed, especially when electric-lighting and haulage are used in the tunnel; or a small compressed-air engine may be used, deriving its supply of air from that used for grouting and ventilation. Where the work is proceeding under compressed air the air-engine may simply have its exhaust carried back through the bulkhead; though as a rule the latter arrangement would require a large engine because of the comparatively low pressure, 20 lbs. to 30 lbs. per square inch, thus available for working it. In long tunnels up to 16 feet or 17 feet in diameter it would, however, be difficult to improve upon the simplicity, handiness, and small cost of the hand-pumps in the shield. Very little time would be gained by the use of mechanical power, though the men would be saved some fatigue.

Grouting by Compressed Air.—In the construction of the Tower Subway, grouting was employed to fill the cavity left by the advance of the shield. This was accomplished by a hand syringe, the lime being mixed with water in a tub. The result was not satisfactory because the grout had to be sufficiently fluid to flow into the syringe and was too fluid for good work, and the pressure that could be applied by the syringe was not sufficient to force it properly home into the spaces to be filled; moreover, this

method of working could only be employed upon a very small scale. The Author, some years later, devised the grouting apparatus first used in the City and South London tunnels, Fig. 17, Plate 2. A cylindrical vessel, capable of withstanding a pressure of 70 lbs. or 80 lbs. per square inch, has through its axis a shaft or spindle working in a stuffing-box at each end of the vessel, and provided at one or each end with a handle outside, and carrying, inside the vessel, a number of paddles. The lime and water are introduced through an opening at the top, having a lid capable of being closed air-tight; and the mixture is discharged by compressed air through a length of flexible hose-pipe ending in a branch and nozzle, the nozzle being inserted in holes in the tunnel lining provided for the purpose. The smaller grouting pans are usually worked by two men; one continually keeps the paddles revolving and opens and closes the air- and discharge-valves, while the other has charge of the branch at the end of the hose. As the space is gradually filled, the holes through which the grouting is discharged are successively closed. Beginning at the lowest hole, grout is forced in until it reaches the hole above it; the lower hole is then plugged and the nozzle applied to the higher, and so on until finally the highest hole, in the key-piece, is reached, and the full pressure is brought upon the grout.

After experiments with Portland and Medina cements and blue lias lime, the Author came to the conclusion that the last was in some respects preferable; and, as it was much cheaper than the cements, he adopted it for the City and South London Railway tunnels. Portland cement has, however, been used in some cases, and for special purposes Medina has been found to work well. The blue lias lime may be mixed with or without sand, and does not set hard suddenly like cement. It can be mixed with only so much water as it will retain in setting, it adheres to the surface of the iron firmly, and when fresh and used hot it expands in setting. No reliance being placed on the surrounding shell for strength, there is no object in having a shell harder than solid London clay. An admixture of sand has not been generally used with the lime, the extra trouble of mixing and handling the two materials is hardly repaid by the small saving in cost over pure lime. It is very important that there should not be an excess of water with the lime or cement, because shrinkage will follow the throwing off of the excess in setting, which will be greatly retarded and be very uncertain. Medina cement for grouting purposes appears also to be better than Portland cement,

but it has not the quality of cheapness as compared with blue lias lime. At the stations of the railway about 2,000 feet in length of the smaller iron-lined tunnels gave place to the larger brick-lined station tunnels, affording an excellent opportunity of observing the condition of the grouting. It was satisfactory to find that the work was in every way perfect. The tunnels were everywhere encased and every cavity had been filled. In some cases where nodules of septaria had been broken and moved by the cutting-edge of the shield, the lime had penetrated through cracks in the stone and had filled the cavity behind the stone, the lime filling the cracks themselves being sometimes not thicker than a sheet of thick paper.

The compressed-air grouting was found to be a very important factor in the work—not only for preventing movements overhead and deformation of the tunnels, but also for several other purposes. Its uses in connection with tunnelling under compressed air to prevent the escape of the air and for making air-tight locks, and in connection with the sinking of iron-lined shafts, are referred to under those heads. It was also found to be most useful in cases where valuable property such as wine vaults had been disturbed by the construction of the brick-lined tunnels. All that was necessary to make the walls quite solid was to point the cracks with cement; and when the pointing had set, to inject the grouting so as to completely fill the cracks, vents being provided for the escape of the air and for observation. In a similar manner a railway bridge elsewhere, cracked by movements caused by the tipping for an embankment, has been restored and rendered secure at a trifling expense.

The supply of compressed air used for grouting also afforded the means for ventilating the long tunnels during construction. It was found that by allowing the compressed air from time to time to escape when it was not required for grouting operations, by a slight opening of the controlling-valve, not only was good air secured at the face, but the temperature was reduced by the expansion of the air, and the usual large pipes and blowers were rendered unnecessary.

Hauling Underground.—In the earlier parts of the work a timber flooring was laid upon long temporary sleepers, resting at their ends upon the iron lining; and the excavated material was run out, and the iron, &c., brought in, by manual labour. Subsequently the flooring was abandoned, the invert was filled with clay, and the work was accomplished by ponies upon a very unsatisfactory road. Electricity will probably be found to be the best

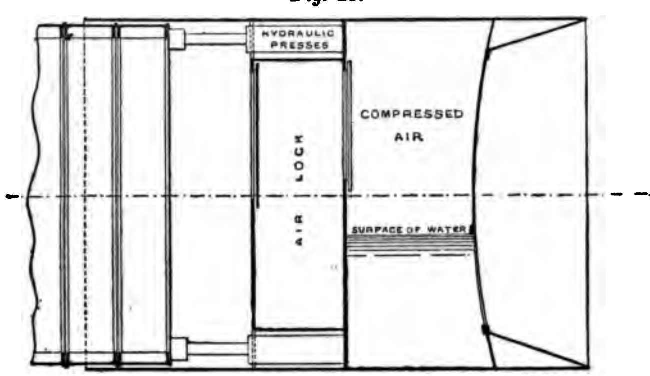
and cheapest means. It has been introduced in the Waterloo and City Railway tunnels, where two small electric locomotives, built by Messrs. Siemens Brothers & Co., do all the traction work.

Tunnelling in loose water-bearing Strata.—At several points on the two sections of the railway compressed air was employed in passing through water-bearing strata. The most notable case was near the south end of the railway at Stockwell, where for a length of about 200 yards the two tunnels were carried through coarse gravel and sand under a head of about 35 feet of water. The longitudinal section of this length is shown enlarged in Fig. 3, Plate 1. For the purpose of this work compressors were erected, and the air was carried a distance of about 300 yards through a 6-inch pipe from them. The tunnels were driven under the normal air-pressure to a point where the cover of clay was reduced to about 5 feet; whence, the air-locks having been erected previously, they were continued under compressed air. It was generally found that the ballast immediately overlying the clay was more open, that is, contained less sand, and that of a coarser character, than in other positions; it was in passing through this very open material that the work was most difficult. The driving of a tunnel is wholly different from the sinking of a vertical shaft under compressed air. In the latter case a uniform pressure of compressed air balances an equal uniform pressure of water; while in the former a practically uniform air-pressure is employed to keep in check a varying pressure of water, the extent of the variation depending upon the height of the face operated upon. For instance, in the Stockwell case, the water-pressure at the top of the tunnel would be that due to a head of about 25 feet; while at the bottom the pressure would be that due to a head of 36½ feet. If the material be close, such as silt or fine sand, there is not much difficulty, provided there be a sufficient cover of material, because the porosity is not so great as to allow of the escape of a large volume of air, while maintaining a pressure sufficient to keep the bottom sufficiently dry. In very coarse sand or, still more, in ballast having but little sand in its composition, it would be impossible to maintain a pressure much higher than that due to the head of water over the top of the tunnel without special appliances and precautions. The difficulty consists in having to work upon, so as to remove, the material from the front of the shield for the whole height of the face, and at the same time to prevent the inflow of a large volume of water, or the escape of an inordinate volume of air. The inflow might involve nothing more than danger to

surrounding structures, where such existed, or it might mean absolute impracticability. In other cases, such as coarse gravel or fissured or very porous rock, it might involve prohibitive expense in pumping. The outflow of air, on the other hand, might, in certain cases, be such as to render tunnelling impracticable, on account of the first cost of plant and the expense of working it. In porous material, therefore, where a large volume of water is to be expected, and the conditions are such as to render pumping impracticable, compressed air is only to be considered if means can be found for preventing its too rapid escape.

The Author many years ago devised means for tunnelling through such water-bearing strata, by working under compressed air with a shield having a face so arranged as to prevent the escape of any large volume of air, *Fig. 18.* The shield was con-

Fig. 18.

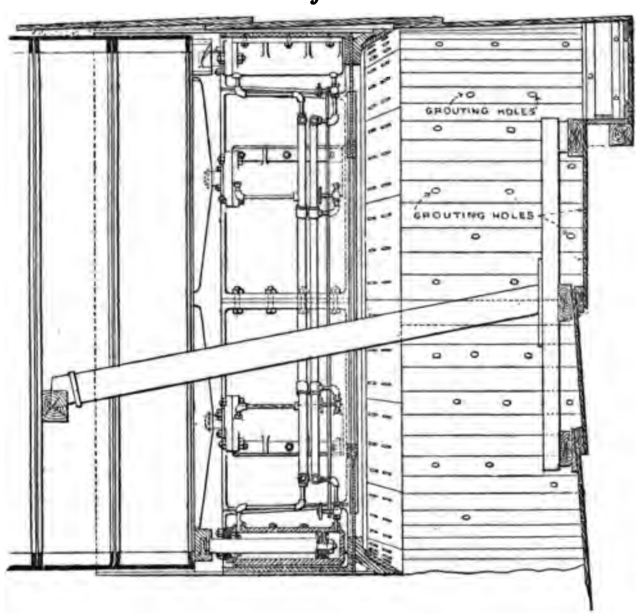


structed for use in the North Woolwich Subway already referred to. It is also practicable, as the Author has proved by experiments upon a small scale, to remove the material from the path of the shield in certain materials by mechanical means, or by a current of water, or by the two combined. In such cases the men might work under a reduced, or even under the normal air-pressure, at depths below that at which they can work at all under pressure. A machine for removing the sand and gravel at Stockwell by mechanical power was constructed and held in readiness for use; but the method first tried was found to work well and was employed throughout.

The shield having been brought to the water-bearing strata, a small heading was driven at the top in advance of the shield, stout poling-boards being used to support the top, resting at one end

upon the forward end of the shield; the heading was then widened out and the polings continued until about three-fourths of the circumference and the whole of the face had been poled, *Fig. 19.* In an ordinary way the polings would not sufficiently prevent the outflow of air, but by frequent injections of lime grout under compressed air, through holes in the polings, as well as through the holes in the iron lining, the escape of air was so reduced that the compressors were not over-taxed. The action of the grout in preventing the escape of air was immediate. The two tunnels

Fig. 19.



Scale, ¼ inch to 1 foot.

were driven in this manner, side by side, under the large mains of the Lambeth and Southwark and Vauxhall Water Companies, supplying a large area of South London, and under sewers and tramways without the slightest disturbance; and this system has since been followed in driving several tunnels under the Clyde and elsewhere in Glasgow through sand, silt, &c. The speed attained under compressed air in the gravel on the City and South London Railway was at each face between 4 feet 6 inches and 5 feet per day of two shifts. The men were found to bear the

compressed air without ill-effect. They were the same men as had worked through the ordinary tunnelling, but the pressure was not more than about 15 lbs. per square inch above the normal.

It is sometimes advisable, and even necessary, to work with an air-pressure below that due to the maximum head of water in the material at the face. For instance, in working in fine sand, by allowing a small inflow of water to take place much below that necessary to carry the sand with it, the pressure of air may be reduced very considerably. This reduced pressure is sometimes of great advantage. The workmen are benefited, and in some cases the work may be more safely carried out, as where there is a comparatively small cover of loose material under a river. In this latter case, a pressure in the tunnel corresponding to that of the head of water at the lowest point of the face, being in excess of that due to the head of water at the highest point of the face, by an amount depending upon the height of the tunnel, or of the portion of the face operated upon, would, in some cases, when the combined pressure of the covering material and the water is less than that of the air in the tunnel, be sufficient to lift or blow up the cover at the face, resulting, probably, in an inrush of water attended with risk to life and other serious consequences; unless other precautions, such as adding weight above or below the material, be taken. It may, also, in more open material, such as coarse gravel, be more economical to pump even the considerable volume of water which would enter with a maximum head equal to the height of the face operated upon, rather than pump the volume of air which would escape through the opening. The average head would be half the height of the opening, and would be independent of the total head of water over the tunnel, the latter being balanced by the air-pressure in the tunnel.

Air-locks.—The first air-lock used was of iron fixed in a bulk-head of brickwork. This was, however, found to be small and inconvenient, and the later air-locks were formed by reducing the size of the iron tunnel by a thick lining of brickwork and concrete, into which two cast-iron door-frames were built, Figs. 20 and 21, Plate 2, leaving a space 12 feet long, 3 feet 9 inches high and 3 feet 9 inches wide for the passage of men and materials. To render this combined bulk-head and lock air-tight, a vertical space of about 3 inches was left in the brickwork at each door-frame, and subsequently filled with Medina cement forced in by the grouting

apparatus under a pressure of about 40 lbs. per square inch. This was found to make an absolutely air-tight barrier. In addition to the main chamber, pipes were built in and through the brick-work of size and length sufficient for passing the temporary rails, pipes, &c., through.

These easily-constructed brick air-locks possess the advantage over the iron air-locks first used of mitigating the chilling effect, due to the reduction of pressure, upon the men, hot from their exertions in the warm compressed air, in their egress. The brick-work, absorbing heat when the lock is open to the compressed air, and parting with some of it during the reduction of the pressure when closed against the compressed air, is found to preserve a more equable temperature than the thin plates forming the walls of the iron locks.

When the compressed air is carried a considerable distance through pipes to the bulk-head its temperature may be sufficiently reduced; otherwise measures should be taken to keep down the temperature of the air in which the men work. A spray of water on the outside of the pipes and receiver has been found to answer well.

The workmen employed in the compressed air on the City and South London Railway did not suffer from partial paralysis or "bends." It is true the pressure was not high—about 15 lbs. per square inch—but from observations on this and other works the Author considers that purity or impurity of air has perhaps more effect than pressure upon the health of the men engaged, provided due precautions are taken as to entrance and exit, and the avoidance of chills. It is noticeable that when tunnels have been driven through almost impervious material, as under the Hudson and St. Clair Rivers, and where consequently the quantity of air pumped has been comparatively small, the cases of "bends" were numerous; while in the gravel in London, both at the City and South London Railway and more recently at the Blackwall Tunnel, with a higher pressure, there were in the one no cases at all, and in the other no fatal cases of "bends." Where tunnelling is proceeding in fine sand or in silt, which are almost air-tight, the delivery pipes from the compressors should be extended to the face as the work progresses, in order that the air used in locking may assist the ventilation in the whole tunnel; and provision should be made for a copious supply of air to be delivered at the face. The more highly compressed air employed for grouting is useful for this purpose and for cooling the air, by expansion through a throttled passage, at the same time. In one

instance, at least, this supply has on a serious emergency proved invaluable. In carrying the tunnels of the Glasgow Subway under the Clyde at St. Enoch's a fire occurred, filling the tunnel with suffocating gases and cutting off the men from the air-lock; and but for the air from the hose of the grouting-apparatus the whole gang would have perished. By lying down and receiving the air in their faces the men were able to live during the several hours that it took to reach them by breaking through from the second tunnel.

Iron Tunnels.

Shape of Tunnels.—The circular section will be found to be generally the most suitable for iron-lined tunnels. In a perfect fluid, with the weight of the lining equal to that of the fluid displaced by the tunnel, a circular section, being free from any bending moments, would be theoretically as well as practically the best. In material not fluid enough to flow round the tunnel lining, the circular section is again the best, because, the material surrounding the tunnel affords abutments solid enough to prevent change of shape, ensuring here also absence of bending strains; this applies to all clays as solid as the London clay, and to all gravels and clean sands. For such materials as silt and very soft clays, the circular section would involve bending strains on the lining; but the more nearly fluid the material, the less severe would be the bending strains.

It is convenient to have all the segments of a ring as far as possible alike and interchangeable; and for this reason alone, it is hardly worth while to depart from the circular section for the saving of a comparatively small quantity of excavation. But in soft material a departure to any considerable extent from the circular section, as for instance, the introducion of a flat invert with sharp junction curves between the invert and sides, would generally involve a considerable addition to the weight of the lining to enable it to withstand the unequal pressure.

Cast-iron tunnels possess several advantages over brickwork or masonry tunnels, even where the latter are practicable. They can be made perfectly watertight whatever the pressure of the water surrounding them may be. They can be made stronger than any brick-lined tunnel because, unlike the latter, high pressures do not involve any appreciable enlargement of the outside dimensions of the tunnel; while in the case of a brick lining, after a certain thickness is reached any addition to the section adds but slightly

to the strength. Where excavation is expensive or difficult, the area required for an iron tunnel being materially less than that required for brickwork or masonry, iron tunnels may be constructed in some cases more cheaply, and in all cases with greater safety. As soon as the iron lining is erected the tunnel is practically complete. Iron tunnels are better adapted for construction by shield, and their construction may proceed with much greater rapidity; and thus in large cities there is less interference with traffic by reason of the entire absence or the reduced number of temporary shafts in the streets.

The following Table gives the ratio of the area of excavation to the internal clear area of tunnel in several cases of brick- and iron-lined tunnels—the clear area being taken as 1.

	Ratio of Area of Excavation to Internal Area of Tunnel.
Brick.	
Railway tunnel in clay, 25 feet wide, double line	1·60
„ „ „ 15 feet wide, single line	1·60
Thames Tunnel, two openings, each 14 feet wide	2·22
Iron.	
City and South London Railway, 10 feet 6 inches internal diameter	1·17
Waterloo and City Railway, 12 feet 9 inches internal diameter	1·17
Glasgow Harbour, 16 feet internal diameter	1·16
St. Clair, 19 feet 10 inches internal diameter	1·17
Hudson (cast-iron), 18 feet internal diameter	1·22
Blackwall, 25 feet inside iron	1·22
„ 24 feet 3 inches inside glazed face	1·30

Combined Iron and Masonry Lining.—Iron alone can be made of the requisite strength and stiffness for the lining of a tunnel of any size. Brickwork or concrete inside the cast-iron should not be relied upon for strength, the two materials being so different in character that they could not be assumed each to take a definite portion of the pressures; and to add internal brickwork for the sake of stiffness is to unnecessarily increase the area of excavation. Any such increase, especially in the case of large subaqueous tunnels, is to be avoided as adding to the difficulty and cost of the work. It is generally desirable, however, to introduce a lining of concrete between the internal flanges of the iron, and perhaps a little beyond to give a smooth internal face, the whole of the iron being thus embedded in lime or cement inside and out. The smooth internal face is also desirable in the smaller railway tunnels as being less noisy and offering less resistance to the flow of air than the unlined iron with projecting flanges.

Since the tunnels of the City and South London Railway were

constructed, a number of other cylindrical iron-lined tunnels have been similarly executed of greater and smaller diameters, for various purposes, in England and abroad. In Table II of the Appendix is given a list of these tunnels. Several small tunnels for gas-supply and drainage purposes, the smallest 4 feet in diameter, are not included in the list.

The Paper is accompanied by numerous tracings, from which Plates 1, 2 and 3, and the *Figs.* in the text have been prepared.

APPENDIX.

TABLE I.—CITY AND SOUTH LONDON RAILWAY.

Date. Half-year ending	Number of Passengers.	Receipts.	Working Expenses.	Train-Miles.	Locomotive Expenses.	Locomotive Expenses per Train-Mile.
		£	£		£	d.
June 30, 1891 . .	2,412,343	19,638	15,521	174,435	6,522	9·0
December 31, 1891	2,862,105	20,244	15,516	188,666	6,099	7·7
June 30, 1892 . .	2,885,262	21,520	15,098	188,944	5,843	7·4
December 31, 1892	3,318,752	22,653	15,390	214,417	6,200	6·9
June 30, 1893 . .	3,251,306	23,159	14,964	217,664	5,754	6·3
December 31, 1893	3,215,151	22,821	14,762	224,101	5,693	6·1
June 30. 1894 . .	3,504,954	24,295	14,990	227,363	5,770	6·1
December 31, 1894	3,454,499	24,253	14,762	230,604	5,672	5·9

TABLE II.

Date of Commencement.	Tunnels.	Number of Tunnels.	Internal Diameter of Iron.		Length of Single Tunnel driven by Shield.	Strata.	Maximum Depth below Water-Level where Subaqueous.	Length of Ring of Iron Lining.
			Ft.	In.	Yards.		Feet.	Inches.
1886	City and South London, Thames, &c. (Electric Railway)	2	10 10	2 6	11,200	Clay, sand and gravel	75·0	19 20
1889	St. Clair River (Grand Trunk Railway)[1] .	1	19	10	2,000	Clay, hard and soft	78·0	18¼
1889	Blackton Reservoir (Stockton and Middlesbrough Waterworks)[2]	1	13	6	142	Shale. .	..	21
1889	Hudson River (railway)[3]	1	18	0	600	Silt, soft .	100·0	20
1890	Fidlers Ferry, Mersey (Liverpool Water)[4]	1	9	0	270	Alluvial beds, clay, silt, &c. .	52·0	18
1891	Kingston, Thames (Southwark and Vauxhall Water)[2]	1	8	4	180	London clay	..	20
1891	Glasgow Harbour, Clyde (roadways and footway)	3	16	0	720	Boulder clay, sand, sand and gravel .	62·0	18
1892	Blackwall, Thames (roadways and footways)[5]	1	25	0	754	Clay, silt, sand and gravel .	80·0	30
1892	Glasgow District Subway, Clyde, &c. (Cable Railway)[5]	2	11	0	6,500	Clay, silt, sand	70·0	18
1893	Mound, Edinburgh (North British Railway)[6]	2	17	6	250	Made ground	..	18
1893	Clichy-Asnières, Seine (drainage siphon) .	1	7	7	500	..	58·0	about 20
1894	Waterloo and City Railway, Thames, &c. (Electric Railway)[5]	2	12 12 23	2 9 0	5,000	Clay, sand and gravel	62·0	20

[1] Heading for masonry tunnel commenced 1886, abandoned 1887. [2] No compressed air used.
[3] Commenced 1879 without shield; 1889 with shield. Work not completed.
[4] Commenced 1888 without shield; 1890 with shield.
[5] Work not completed. [6] Not subaqueous. Compressed air used.

Discussion.

r Benjamin aker. Sir BENJAMIN BAKER, K.C.M.G., President, said the members were indebted to the Author for a very interesting Paper, which he had no doubt would be followed by an equally interesting discussion. As a Member of Council the Author was disqualified for receiving a medal or premium, and the only thing that the members could award him was a vote of thanks, which he felt sure they would give with all sincerity.

Mr. Mott. Mr. C. G. MOTT remarked that a year or two after the City and South London Railway Companies' Act had been obtained he had been approached with the suggestion that he should take the Chair of the Company and endeavour to get the work carried out. After the experience obtained in connection with the Thames Tunnel he had not been hopeful that the work would be successfully accomplished; and it was not until he had visited the Tower Subway that he had been satisfied that the work was practicable. It had shown him at once that the principle which the Author had proposed had been previously adopted with success. He had then felt that the carrying out of the work was a practical measure under the able control of the Author, aided by Sir Benjamin Baker and Sir John Fowler. It had been his fortune to be connected as a director with the companies that had carried out during the last twenty years three great tunnelling operations in England—the tunnel under the Severn, carried out by Sir John Hawkshaw; the tunnel under the Mersey, by Sir Douglas Fox and Mr. Francis Fox; and the present tunnels, by the Author. He had been struck by the wonderful power exhibited by the leading engineers of the country in meeting all the difficulties arising in the course of construction. In the case of the Severn Tunnel the influx of what amounted to a river of water had been attended with the greatest difficulty, but it had been overcome, and the tunnel had been worked for years, and was now one of the essential parts of the Great Western Railway. The Mersey Railway, if not financially successful, was carrying a large traffic between Liverpool and Birkenhead. In regard to the City and South London Railway, the many points of difficulty which had arisen had been overcome by the ability of the Author and the extreme thoughtfulness he had bestowed upon every question of the construction.

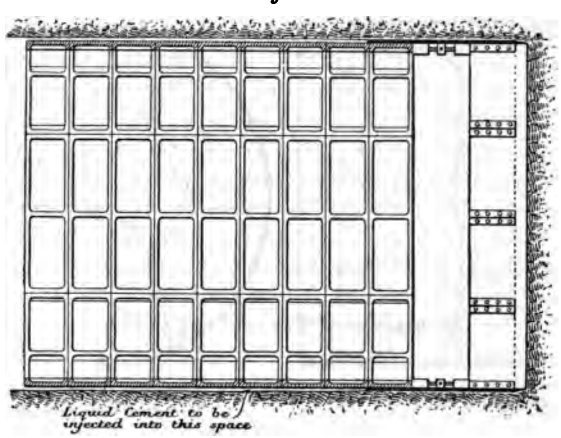
The only method of crossing rivers used by our ancestors had been by boats or rafts. Then had come the discovery of bridges, and so greatly had they been valued in the middle ages that it had been regarded almost as a religious act of devotion to construct one. For centuries men had constructed bridges and had gradually improved them till the time of Telford and his Menai Suspension Bridge, and finally the great Forth Bridge had been constructed. Bridges might now be considered to have arrived at the climax of their construction, and it was now a question, considering the increased use made of rivers, whether it was not still more desirable to pass under them by means of tunnels. That method had been successfully tried by Brunel, but only with the greatest difficulty and at the greatest cost. In the case of the Severn and the Mersey the system had been adopted at great cost, but in the case of the Thames the cost was marvellously small, for he did not think that the amount expended on both of the tunnels of the City and South London Railway under the river exceeded £30,000. In view of the difference in cost by adopting the simple method which the Author had employed, great results might be expected from it in the future. The question had been often raised of constructing tunnels under the sea, such as the proposed Channel Tunnel, and that between England and Ireland. To the latter he thought there could be no possible objection, and he hoped that it would be before long carried out. The difficulty that had arisen was in the working. In a Paper[1] by Mr. Bateman and Mr. J. J. Rèvy the whole question of the Channel Tunnel had been discussed, and a proposal had been made for working it by atmospheric pressure by means of the tide. That appeared to him an ineffective and cumbrous mode of working, although it was very ingenious and worthy of the great engineer who proposed it. He thought that the question had now been solved by the introduction of electricity. There was no difficulty in running an electric train through any tunnel of that length, and he thought it was time that some steps were taken to try a long tunnel of that description between England and Ireland. Mr. Mott.

Mr. CRAWFORD BARLOW rose with a view of adding a few facts which had come to his knowledge, from being in possession of the papers of his uncle, the late Mr. Peter William Barlow. In 1863, when Mr. Barlow was sinking the cylinders of Lambeth Bridge, Mr. Barlow

[1] Report of the British Association for the Advancement of Science, 1869, pp. 206–209.

Mr. Barlow. the idea occurred to him of propelling cylinders horizontally for the purpose of tunnelling. Accordingly, in 1864, he took out a patent for constructing tunnels, where they were to pass under rivers, or under towns and places where the upper surface could not without serious injury be broken up or interfered with, by means of a cylinder of somewhat larger diameter than the external diameter of the intended tunnel, made preferably of wrought iron or steel. The forward edge of this cylinder was made comparatively thin, and the earth was continuously removed from within it. The cylinder was from time to time forced forward a short distance to admit of a ring of iron being put together within its inner end, of a strength suitable for

Fig. 29.

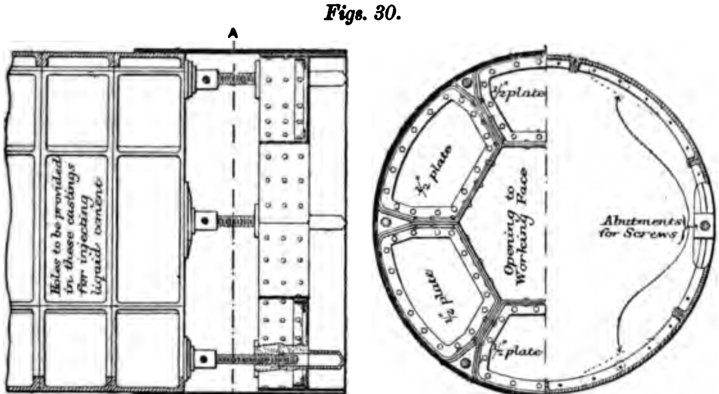


Scale, ¼ inch to 1 foot.

forming a permanent lining to the tunnel. It was desirable that the thickness of the iron of the cylinder should be as small as possible, in order that the space between the outer surfaces of the rings and the earth which surrounds them might not produce subsidence in the surface of the land above. In *Fig. 29* was shown a longitudinal elevation, partly in section of a portion of a tunnel composed of a succession of rings of iron put together with screw bolts and nuts, and also of the cylinder, by and within which the work of removing the earth was performed. If the soil was weak, provision might be made for the use of poling-boards. The space left between the earth and the exterior of the tunnel might be filled by injecting fluid cement. In 1867 Mr. Barlow wrote the pamphlet to which the Author had referred; and in 1868 he

took out another patent, in which he stated that he formed the cylinder with a transverse partition or end, having through or below its centre an opening, which could be either partially or entirely closed as required. As the cylinder was forced forward through the ground, the earth in front of the end of the cylinder was worked away and taken into the interior of the tunnel through this opening. By this arrangement, should the water at any time break into the tunnel, the upper portion of the interior of the tunnel might at all times be kept supplied with air under pressure, as the closed end would prevent the air from escaping. As soon as the tunnel had been pushed forward sufficiently to stop the leakage of water into the end of the tunnel, the pressure Mr. Barlow.

Figs. 30.



LONGITUDINAL ELEVATION. FACING SHIELD. FACING TUNNEL CROSS SECTION A.B.

Scale, ¼ inch to 1 foot.

of air in the tunnel might be relieved. In 1868 the prospectus of the Tower Subway had been brought forward, and in it the report of the engineer referred to arrangements having been made for air-pressure if necessary; but in driving the tunnel it had passed entirely through the clay, and there had been no necessity for the application of this process. The subject was subsequently pursued further by Mr. Barlow, and in 1870 he obtained an Act for the Southwark and City Subway, which was practically the same route as the first part of the present line. A company was formed in 1871, and in the prospectus it was stated that the construction was to be on the same principle as that of the Tower Subway, except that the diameter of the tunnel was to be half as large again—that was the same size as the present City and South London tunnel. The Company, however, could

Mr. Barlow. not be financed, and in 1873 an Act of abandonment was obtained. The present railway had evidently followed on the same lines. The main principles of the two patents of 1864 and 1868, namely, (1) that of the tunnel with cast-iron lining; (2) the wrought-iron or steel cylinder overlapping it; (3) the diaphragm with an aperture which could be closed in case air-pressure was required; (4) screws or hydraulic presses for propelling the cylinder or shield forward; and (5) apertures in the cast-iron lining for injecting the fluid cement in the space outside the lining of the tunnel vacated by the shield, were all included in the design made by Mr. Barlow for the shield at the Tower Subway shown in *Figs. 30*, and it is thus evident that this shield was the progenitor of those used in the City and South London Railway, and, in fact, of all the shields in use in the various subways now being constructed; and he was therefore surprised to find that the Author had not referred at all to the work connected with this mode of tunnelling which Mr. Peter Barlow had done before him. At the same time he congratulated the Author on the wonderful development which had been made in this special mode of subaqueous and sub-metropolitan tunnelling.

Mr. Price-Williams. Mr. R. PRICE-WILLIAMS observed that the apparatus and the method which had been described were destined to have a great field of operation, not only in subaqueous tunnelling, but in many other situations where ordinary tunnelling was impracticable, as, for example, in the case of the construction of subways in the Metropolis to relieve the great congestion of traffic to which the Author had referred. He considered that the time had now arrived when recourse should be had to the admirable system described in the Paper, without which the great and growing congestion would assuredly interfere with the future growth of London, which was not only the metropolis of the kingdom, but the great commercial centre of the world. In an interesting Table the Author had drawn attention to the remarkable growth of traffic, and the contrast which it afforded to the increase of population. The figures were certainly startling, and, as the Author had admitted, he had largely understated, for reasons which he had explained, the enormous amount of passenger traffic in London. He had, for example, entirely neglected the very large traffic on the North London and other railways, besides which there was the great increase in the suburban traffic of the principal railways having their termini in London. It was impossible to say what it would all mean in the course of a few years. In a recent report furnished by a commission on another subject—an aqueous

rather than a subaqueous matter—an estimate had been made of the population of the Metropolis, not the Metropolis described by the Author—the Registrar-General's district—but of "Greater London."[1] He wished to point out the fact that the congestion of traffic to which he had alluded was in a great measure due, paradoxical as it might appear, to the great work of which Sir John Fowler and Sir Benjamin Baker were the engineers—the Metropolitan Railway. It was a remarkable fact that up to the time that the principal main lines of railway connected up with London, the population had continued to congest to such a dangerous degree, that, had it continued longer, it would undoubtedly have seriously affected the health of the inhabitants and prevented the development of the Metropolis; but happily by the construction of the Metropolitan, Metropolitan District and other suburban railways, a relief was found—to use the language of a writer of a leading article in the *Times* on a Paper which he had read before the Statistical Society, on the population of London—"From the time the railways connected up with London, there had commenced an overflow of the population from the congested district which had rendered London safe, and it was really owing to the centrifugal effect of the outflow of the population to the outlying districts of the metropolis that its enormous growth was mainly due." The population of the metropolitan outer area was now nearly six millions, and unless some means were devised, like the admirable method described by the Author for subways in London, its growth would be arrested. He hoped that the attention of the engineering profession would be directed to the large employment of that admirable system for the purpose. He was glad to know that already a commencement had been made in the City and South London Railway. Having had an opportunity of examining the works during their progress, he was glad to congratulate the Author of the Paper on the successful way in which he had surmounted the numerous engineering difficulties he had to contend with; but no one could more fully realise than the President himself—who with Sir John Fowler had been associated with the Author in the works—the energy, the conspicuous ability, the judgment and the resource which the Author of the Paper had displayed in carrying them out. Mr. Price-Williams.

Mr. S. J. WILDE was one of the few who remembered as a boy seeing the working of the old Thames Tunnel, and he hardly Mr. Wilde.

[1] "Report of the Royal Commission appointed to inquire into the Water-Supply of the Metropolis," 1893, p. 11.

Mr. Wilde. thought, in the observations that had been made, sufficient justice had been done to the difficulties under which that work had been constructed. By some mistake it had been carried too near the surface, and a quantity of pure liquid mud had come through, so that it could only be worked by filling up from the surface and tunnelling through—a matter of considerable difficulty. He might mention that the tunnel had been complete in the first instance, and afterwards a dividing wall had been erected quite solid, and at a subsequent time arches had been cut through, which still remained. A solid wall had been made in the first instance to give sufficient strength to the roof. For keeping the tunnel dry, in spite of any weeping through the brickwork, rings of tiles similar to roofing tiles, placed at intervals of about the same width as the tiles, had been affixed to the sides and roof of the tunnel. These were covered with similar tiles placed horizontally, and a series of passages were left, through which moisture could run down into the drains under the centre of the tunnel. All being then covered with cement the tunnel had been rendered perfectly dry.

Mr. Fitzmaurice. Mr. M. Fitzmaurice wished to call attention to the word "subaqueous" as applied to tunnelling. Its meaning was quite clear, but there was a great difference between a tunnel driven through water-bearing strata, and a tunnel with say 20 feet of clay between it and the river. When a tunnel was said to be subaqueous, it was generally supposed to be of a more or less difficult character, although under certain conditions it might be of the simplest possible construction. The majority of tunnels were to a certain extent subaqueous. It had been stated by the Author that the borings taken from time to time disclosed the fact that the City and South London Railway was subaqueous over nearly its whole length, although water difficulties had been encountered only over a very short length. In a reference to the tunnel constructed with a shield at Cincinnati, it was stated that this tunnel was not subaqueous although it went under two canals. It was, therefore, difficult to decide where to draw the line in the use of the word "subaqueous," and he thought that some word should be applied to tunnels which would mean that difficulty had been encountered in connection with water, instead of using the word "subaqueous," which was more or less indefinite. He observed that near King William Street the tunnel passed round a curve of 140 feet radius. It would be interesting to know whether that portion of the line was in London clay, or in water-bearing ballast. Of course, if the excavation could be taken out for some way in

Mr. Fitzmaurice.

front of the shield, it would be easy to bring it round a comparatively sharp curve; whereas, if the shield had to cut its own way to any extent, there might be a difficulty in bringing it round a much flatter curve. He asked if special castings were used for curves so sharp as that mentioned. The Tower subway was interesting as being the first tunnel in which cast-iron was used and where the shield was shoved forward as a whole. The subway under Broadway, New York, built by Mr. A. E. Beach, deserved mention as being the first in which hydraulic rams were used to propel the shield forward. The face of this shield was divided into several horizontal floors, so as to break up the natural slope of the material. He thought the Author would have referred to the tunnel between Manhattan, New York, and Long Island, which had been recently completed by Mr. C. M. Jacob. In this case a shield and cast-iron lining had been used in constructing the portion through soft material, and an air-pressure of 48 lbs. was required for a considerable time. The effect of such a high air-pressure on the workmen was very serious, and some deaths had occurred from this cause. He quite agreed with the Author that a constant change and an ample supply of air was essential to men working in compressed air to keep them in good health. With reference to the patent taken out in 1830 by Lord Cochrane, he could not agree with the Author that the use of compressed air was only contemplated for driving tunnels through materials impervious or nearly impervious to water and air. In the specification of this patent Lord Cochrane stated that in certain cases the air-pressure would have to be equal to the pressure of a column of water of the same height as the surface of the river was above the excavation in the tunnel, thereby implying that the tunnel was in direct communication with the river; and he went on to say, "But it will not be necessary at all times to keep up such a great compression of air in the excavation; only at times when the ground which is in progress of excavation is so loose that there is danger of an irruption of water from the river. When the ground is very firm and safe the degree of condensation of the included air may be greatly reduced." The tunnel started by the Author at Woolwich was, he thought, one of the most interesting things mentioned in the Paper. It was the first tunnel in which compressed air was used, and the arrangements made by the Author for the purpose of driving this tunnel seemed to be very complete. He should like to ask what the size of this tunnel was, and whether the hydraulic erector designed for this work was carried on the shield or was independent of it. The first hydraulic

Mr. Fitzmaurice. erector had been, he believed, actually used at the Hudson tunnel, and the first erector carried at the back of the shield was at the St. Clair tunnel; in the latter case, however, the erector was worked by hand-power by means of suitable gearing. The erectors used at the Blackwall tunnel were carried at the back of the shield and were worked by hydraulic power. A sketch of the erector proposed for the Woolwich subway would be of great interest. The Author had stated that cast-iron tunnels could be made stronger than any brick-lined tunnel, because, unlike the latter, high pressures did not involve the enlargement of the outside dimensions of the tunnel. That might be true to a certain limited extent, but if there were high pressures the cast-iron flanges would probably be made much deeper, and therefore it would be necessary to increase the outside diameter. With reference to the comparative merits, as regards cost, of air-locks made of brickwork with door-frames built in, and those made of iron and fixed in a brick bulkhead, he thought any advantage which either might have depended on the length of lock required, and the size of the tunnel. In either case a certain minimum thickness of brick bulkhead was necessary to stand the air-pressure in the tunnel. If the length of lock required was a little less than this minimum a brick lock would be cheaper, but if it was longer an iron lock would probably be cheaper, as if the latter were used the lock might project on each side of the brick bulkhead, whereas with brick lock the brick bulkhead would have to be extended the whole length of the lock and even a little beyond so as to take the door-frames. The cost of this extension of the brick bulkhead would depend on the relative areas of the lock and the tunnel. The advantage of a safety screen in the shield was very great, but he did not think that by means of grouting alone the joint between the cast-iron lining and the shield could be kept tight while moving the shield, and unless this was done the safety screen was inoperative. With reference to the shape of iron tunnels there was no doubt but that the circular was, as a general rule, the best. He did not, however, agree with the Author that in a perfect fluid, with the weight of the lining equal to that of the fluid displaced by the tunnel, a circular section was theoretically free from bending moments. On the contrary, there would always be bending moments under such conditions, more particularly in large tunnels at comparatively small depths below the surface of the water. It was impossible, whatever the surrounding material might be, to eliminate bending stresses, and these must always be of a more or

less uncertain character, as any calculations with regard to them would have to be based on assumptions with regard to the character and natural slope of the surrounding material. Nothing had been said in the Paper with regard to cost. Indeed, it was very difficult to find out the cost of any tunnel work. In the report recently made to the Board of Rapid Transit Railroad Commissioners for the City of New York on Rapid Transit in Foreign Cities, by their engineer, Mr. W. B. Parsons, he had found prices stated at which several tunnels had been let to contractors in this country; and, as the price for the work with which he was connected, viz., the Blackwall tunnel, was correct, he assumed the others were also. Among these were: Mr. Fitzmaurice.

	External Diameter.	Per Lineal Foot.
	Feet.	£.
Glasgow District Subway	12	27 for double tunnel.
Glasgow Harbour Tunnel	17	27 for one ,,
Waterloo and City Railway . .	13	32 for double tunnel.
Blackwall Tunnel	27	125 for one ,,

The prices were given as for excavation, supplying the iron lining and putting it in place, and the price for the last tunnel referred to that portion under the Thames and for a short distance on either side. From the figures given in the Paper, the Tower Subway, including the shafts on each side, appeared to have cost only £7 10*s*. per lineal foot. The cost of the tunnel constructed under the Seine at Clichy, by Mr. Berlier, which was about 8 feet in external diameter, had been stated as £29 per foot run, including the shafts on each side of the river. In this tunnel an air-pressure of 30 lbs. per square inch had been used, and great difficulties had been experienced owing to the broken and varying nature of the ground.

Mr. ALEX. R. BINNIE thought the members must feel deeply indebted to the Author, inasmuch as the Paper described the first practical attempt on a new line to solve the difficulties of the transfer by locomotion of the vast populations of our great towns. It was distinctly not a theoretical but a practical contribution to the solution of that problem; still further, it was of value as showing within what limits locomotion by such means could be carried out, for there could be no doubt that had the whole of the 3 miles 1 furlong of the City and South London Railway to be constructed under the difficulties which the Author encountered in the gravel bed at Stockwell, although it would probably have been an engineering, it would not have proved a financial success. Mr. Binnie.

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Mr. Binnie. It seemed that all the success of works of that kind depended upon the ability to carry the line or lines through an impervious watertight clay. As soon as gravel saturated by water was reached, difficulties occurred which rendered the construction exceedingly costly—so much so, he feared, that, except for short distances, the expense could hardly be repaid by the ordinary traffic on a long line. In contemplating the construction of such a line as that described, the most difficult—or what might be considered by the uninitiated the most difficult—part was the passage under the River Thames. In the case of the Tower Subway, of the City and South London Railway, and of the line now under construction, the Waterloo and City Railway, those tunnels were matters of comparative ease. They were constructed in the impervious beds of the London clay, and, as he thought it would be admitted, they were as easy to construct as would be a tunnel under Primrose Hill. It was only when that mode of construction approached a bed saturated with water that difficulties really commenced. The advantages of a shield in the case of a railway in clay of that kind were reduced almost to the lowest dimensions. A shield could be worked with a perfectly open face. If a large bed of septaria or nodular concretion occurred in front of the cutting-edge, there was not the slightest difficulty in running out a small heading, or in sending a man ahead of the shield to remove the obstruction. No compressed air was required, and the use of the shield in clay of that kind was confined to the two functions of supporting the roof during the period of inserting the rings and to the facility of pushing it forward and so avoiding timbering. In speaking of shields he was reminded somewhat of the remarks of Sir Benjamin Baker in his Presidential Address,[1] in which he had pointed out that engineers were all more or less dependent—most of them more than less—on the work of their compeers or their comrades, the contractors, and possibly also in some cases very much dependent on the work of their predecessors. He ventured to say that in the early part of the century there existed a mechanical genius, to whose efforts in the direction under consideration engineers were all very largely indebted. He should like to go back to the year 1818, and to take up a patent specification, No. 4202, by Marc Isambard Brunel, with the drawings accompanying it. It was a specification for forming tunnels or drifts underground, and in the drawings there were shown, among many other things, a circular wrought-iron shield

[1] Minutes of Proceedings Inst. C.E., vol. cxxiii. p. 3.

proceeding in front of the excavation. Certainly it differed from modern shields in being formed in sections, in cells, as the specification stated. The shield had an iron plate which overlapped the main structure. That main structure, the tunnel, was composed of cast-iron rings, and the whole shield was shown as being projected forward by hydraulic presses. Looking at the shield, he must say that it contained within itself, not the germs only, but all the important features of the shields—of all modern shields in use at Blackwall or elsewhere. The idea was not latent, but was actually described in the specification. Certainly, when Brunel, between the years 1825 and 1842, had to construct the tunnel under the Thames between Wapping and Rotherhithe, he had not adopted that mode, and, with the knowledge of the present day, it could be understood why he did not do so. The mechanical appliances of his time would hardly go to the length of constructing a tunnel which in the specification he pointed out must be, to be of any good, about 20 feet in diameter to accommodate the two lines of traffic. When, however, he had constructed the tunnel he had used a shield. It was indeed a rectangular shield, composed of separate cells with iron plates overlapping the brickwork, and it was thrust forward by screw-jacks, abutting upon brickwork, of which the tunnel was composed; and he ventured to say that it was only those who had to construct a tunnel under a great river like the Thames who could fully appreciate the difficulties, the dangers, the courage and the perseverance which must have been required during that long period of seventeen years in which Brunel was engaged in that wonderful feat of engineering. Passing on to the middle of the period that elapsed between 1825 and 1842, he came to the year 1830, and again he would refer to a specification No. 6018 of a remarkable genius, Admiral Sir Thomas Cochrane (subsequently Earl of Dundonald), who, fully cognisant of the difficulties under which Brunel was working at the Thames Tunnel, took out a specification for an apparatus for excavating, sinking and mining, in which he displayed a drawing of a shaft sunk on the border or margin of the river, and a tunnel projecting out under the river. It was not stated in Sir Thomas Cochrane's specification that it was for the purpose of assisting Brunel, but any one who had read the literature of the times and looked at the specification could not but see that when he uses the words "being a similar undertaking to that which is now executing beneath the river Thames at Rotherhithe," that the two men were working in the same direction. What is found in the specification? A shaft to be sunk by pneumatic pressure, an

Mr. Binnie.

Mr. Binnie. air-lock at the top, air-locked at the bottom, a horizontal drift or tunnel running out under the river, also air-locked. He asked any dispassionate person who read that specification to say that Sir Thomas Cochrane had not in his mind the working of the same tunnel that Brunel was engaged upon only under compressed air. He could not trace out that compressed air was used in the construction of any work until the year 1839 at Chalons in France in passing through a bed of quicksand. He had some considerable difficulty in fixing the period at which compressed air was used in driving a horizontal adit or tunnel. As far as he had been able to ascertain, it must have been about the year 1871 or 1872. He had not been able to obtain access to all the papers in the Foreign Transactions, but he believed that about 1870–3 tunnels had been driven in America, not very long ones, under compressed air. In the two patents to which he had referred was seen the beginning of the work they were contemplating. What was involved in the work of compressed air? First it was necessary to determine in some way the greatest depth at which to work. He was now supposing that the work was to be performed in a stratum of gravel or some other material which was saturated with water. He did not think that, with due regard to economy of money and life, it was possible to work at a very much higher pressure than 35 lbs. to the square inch above the atmosphere, that was with a head of water of 80 feet. He should approach the construction of works under a greater pressure than that, only with considerable diffidence. With regard to the upward limit, what was that to be? He was now contemplating carrying a tunnel under a river with a gravelly bed; the bed of that river could not very well be approached with the work of construction within 5 feet or 10 feet. The minimum depth at the Blackwall Tunnel was 5 feet 6 inches, and he did not wish to repeat that experiment. Passing to the two next patents of 1864 and 1868, taken out by the late Peter Barlow, those patents had been most carefully described by Mr. Crawford Barlow. He would make no comparisons, but he would merely ask the members to compare Mr. Barlow's descriptions in his patents with those of Brunel and Cochrane. With a modesty which very well became him, the Author had hardly told the whole history of the subject or stated in what way he was connected with the advance of that mode of construction. The subway at the Tower had been designed about the year 1864 or a little later by Mr. Peter Barlow, who had written a pamphlet, but failed to obtain any reputable contractor who would carry out the work. Although an engineer, the Author, formerly his pupil or

assistant, came forward, and at his own risk undertook the construction of the work as contractor for Mr. Barlow, thereby proving much more effectually than by the taking out of any patent the practicability of that mode of construction. He thought that considerable honour was due to the Author for having come forward at a very critical time to prove the practicability of a mode of construction which had been initiated by Brunel and seconded by Mr. Peter Barlow. That was not the time or the place to say more with regard to the Author of the Paper; they all knew him well, and also knew how much they were indebted to him for many of the improvements that had been adopted in that mode of working. He would ask the members to regard it as an engineering advance, and not as a matter of controversy as to who was or was not the originator. They could all afford, without derogation to their own susceptibilities, to bow in all honour to their predecessors who gave them, many years ago, ideas by which they were now profiting. Turning from the past history of the work to future prospects, he looked with great confidence to this method of work in large towns, which, under proper limitations, he thought would be a fruitful source of further improvement in that great and overpowering problem—how to deal with the subject of moving great masses of population. He was glad to see, from a not very rapid legislature, a suggestion which he thought might aid them in that direction. There had sat in the session of 1892 a joint committee of the two Houses of Parliament on the electric and cable railways of the Metropolis. All who had had to do with communications in the Metropolis, or in any other large town, knew that more than half the expense—much more in some cases—was due to the exorbitant prices demanded for land. In the fourteenth recommendation of the Committee there were some words which might assist them in future:—"As to the terms and conditions upon which the subsoil should be appropriated, the Committee report that, in the case of private property not under public streets, it appears to them to be desirable that companies should be allowed to acquire a way-leave, instead of purchasing the freehold of the land, subject to the terms of the Lands Clauses Act as to compensation." That, in other words, merely repeated what were the present powers of the London County Council for constructing sewers. It could make a sewer anywhere that the public interest required; it need not purchase the fee-simple of the land; it might pay for an easement, and it certainly would have to pay for any damage done to the tenants at the Mr. Binnie

Mr. Binnie. surface. But with railways such as those they were dealing with, carried at such depths as those contemplated by the Author, where vibration was not to be detected and rumbling was not heard, compensation would be small, except where they came across an establishment like that at South Kensington, in which delicate magnetic or electric instruments were concerned. In that case, no doubt, an electrically-worked railway of that description might be utterly subversive of the accuracy which the establishment desired to maintain. But, putting highly scientific research out of the question for all ordinary purposes, railways of that description could, he felt sure, be carried without nuisance or injury under any ordinary private property with perfect safety. There was a detail in the construction about which he did not think there would be any dispute, that was that the Author had designed one of those little adjuncts which added so much to the success of such undertakings, viz. his pneumatic injecting apparatus to fill up the inevitable vacuity which must exist between the lining of the tunnel as the shield went forward. That was one of those little things, taken with electric light and compressed air, which made the modern working of the system so exceedingly easy as compared with what it must have been in times gone by. He felt tempted, although that was not the proper time for the purpose, to dilate more fully on the difficulties of that kind of work. He ventured to hope that at no distant date Messrs. Hay and Fitzmaurice, the resident engineers of the Blackwall Tunnel, would favour the Institution with a Paper on that work; and he thought that when it came to be placed before the members, they would be able much more fully to discuss the difficulties under which that description of work could be carried on.

Mr. Lewis. Mr. W. B. Lewis thought the Author had, in his very modest statements, withheld information which the members would like to possess. A few years ago it had been his duty to look into the construction of the City and South London Railway, with a view to discover what damage it had done to the neighbourhood through which it passed, and questions had been raised upon which a great deal of light had been thrown by subsequent experience. He felt much disappointed that Mr. Binnie had not given some information on that point in connection with the work on which he was engaged. But he desired to ask a question which was of far more interest than the history of the subject. He might say, in passing, that the Author was entitled to much greater honour for adopting other people's ideas, and putting them into practice, than he would be for

recording any specification that might have been laid aside for Mr. Lewis. years before a practical man could be found to apply it. They were greatly indebted to the Author for working out, in a most able and resourceful way, all sorts of expedients for getting over the difficulties of this system. The first thing that had struck him, was that the Author had made a small 6-foot 6-inch passage under the Thames, through clay at the Tower, and he never heard that any property was displaced, or that any damage was done in consequence. The 10-foot 6-inch railway under the Thames near London Bridge had then been constructed by the Author, and some little damage had been caused to the buildings at the Hibernian Wharf. In connection with the same railway, the stations required a much larger tunnel, and considerable damage had resulted. He should be glad to know how far the increase in size accounted for the extra damage. He was afraid that the Author would say that those large tunnels could not be made in the same way, and were not made with a shield. At Blackwall a tunnel 27 feet diameter had been made, and he should like to know whether there had been settlements near any portion of the approaches. Difficulties had occurred—comparatively trivial ones—under the bed of the Thames. To engineers acquainted with tunnelling in clay, it must be apparent that that was the simplest method of overcoming the chief difficulty met with, namely, to cover the clay up speedily after it was opened. In excavating a length of tunnel, before the brickwork could be got in, the clay began to swell, and a great deal of damage was done. In the present case, the clay had been excavated and the lining got in before any such damage could follow. He also wished to ask whether the filling with grouting had been fully tested, and with what effect. He had seen a piece of lining of the grouting taken from one of the tunnels made with a shield. It was a large piece, and looked like a piece of thick plaster. In picking it up he had expected to lift a great weight, but was surprised to find how light it was—so light that it could not have had much density. He wished to know whether that was strong enough to stand the pressure of a great mass of clay. If it had been in a clay tunnel, would the clay compress it in time, and cause movement? The movement was slight compared with that produced after removal of timbers. But he should be glad to know whether the matter had been tested. If the plan described in the Paper was to be considered with a view to general use, it would be governed very much by the cost. It had been spoken of by Mr. Binnie as if its

Mr. Lewis. adoption for any great length of tunnel was out of reason; and he should be glad to know whether that was the case—also whether it would avoid the great pumping necessary with the ordinary practice. In the case of the Blackwall Tunnel the approach at the Deptford side had not been made under pressure, but an immense amount of pumping was necessary, and the whole district was disturbed. The place was not much built over, but some new cottages had been erected by the London County Council, all of which had moved; and a great deal of inconvenience had been felt through the subsidence of the neighbouring soil. Would the system of working with atmospheric pressure do away with some of the pumping, and how would the cost of the atmospheric pressure compare with the cost of pumping, having regard to the damage done in the neighbourhood?

Mr. Binnie. Mr. ALEX. R. BINNIE said that the settlements referred to by the previous speaker had not taken place. The tunnel had passed within a few yards of some large buildings which had been erected thirty years ago by the Blakeley Ordnance Company, and no damage had resulted. He had not said that the work could not be constructed, but merely that it could not be constructed economically if the whole 3 miles were similar to the 200 yards of gravel bed at Stockwell.

Mr. Sewell. Mr. W. SEWELL stated that the drawing of the shield had been placed in his hands by the Author, and he had constructed and put it to work on the undertaking in question. Having used twelve shields during the extended period of the construction of the line, he wished to bear testimony to the fact that very little trouble had arisen with regard to repairs and breakdowns. The only trouble that had occurred in the way of keeping the shields in working order was in the renewal of the leathers in the hydraulic presses, and that, he thought, was chiefly attributable to the grit and dirt getting into the water-tanks from which the pumps were supplied. In a shield constructed a little later under his supervision for the Blackton Reservoir in Yorkshire, the water-tanks had been made with closed tops, with a gauge-glass at the side, as in the case of a steam-boiler, so that the men could see whether there was water in the tanks or not. That prevented the workmen from putting in their tools, &c., and the wearing of the leathers gave no trouble whatever. With regard to the shield, it was perfectly true that when it was put to work in an impervious stratum like London clay there was little difficulty in working it. The process went on regularly, and there was one great advantage connected with it, from a

constructive point of view, which had not been pointed out—only one set of men was required, and they were practically unskilled labourers. He should have no fear in training any ordinary intelligent labourer to take any part in working the shield in a week. The tunnel-bricklayer was thus entirely done away with, and engineers who had anything to do with the construction of a tunnel would know what a great advantage that was. The wages of those men in the country were 1*s*. 6*d*. an hour, and there was great difficulty in keeping up the supply even at that figure. Whatever might be the merits of the shield—and he considered them to be very great—he believed that the grouting apparatus (of which there was no question the Author was the originator) was undoubtedly a very important accessory; he considered that without the grouting apparatus the shield would be practically useless. Unless the cavity formed by the shield in advancing was at once filled by the grout there would be settlement and crippling of the lining, which would soon lead to serious trouble. He thought that the immunity from settlement which had been enjoyed along the line of the iron-lined tunnels was almost altogether due to the grout apparatus. A question had been raised as to the liability of the grouting material to shrink under pressure. When the grout was injected it became, within an hour, quite as hard as the London clay itself, and in a day or two as hard as concrete. That being so he could not see that there was any fear whatever of shrinking arising from the grouting. From the specimens that had been taken out of that portion of the iron tunnels driven as temporary headings through the sites of the stations, there was not the slightest crevice of any kind but what was thoroughly filled, even to the thickness of a sheet of paper, by the grout. In the sinking of the staircase shafts, which took place a little later than that of the main shafts, after they had been carried into the London clay and sunk to a depth beyond which it was not safe to push them, the ground had been cut out, lined with cast iron, and grouted up solid by the grouting pan with great success. The work was carried out quickly and expeditiously, and without the slightest subsidence or crippling of any kind whatever. He should have no hesitation in carrying down a shaft of that kind through almost any strata, to any depth at which compressed air could be used, in that manner. All that was necessary was, in putting in the closing segment, to excavate a little bigger than for the rest, to draw the segment inwards into place and grout the cavity so left with the grouting pan. That being done, the shaft was left perfectly solid, and had given

Mr Sewell.

Mr. Sewell. excellent results. In constructing air-locks for the wet portion of the tunnel, the first lock erected had been built without grouting, and it had been a long time before it could be rendered perfectly air-tight. There was great difficulty in building brickwork which was practically air-tight. In the second lock, a cavity of 3 inches had been left in the fore part of the lock in which pipes were inserted. That was blown full of grout afterwards by the grouting apparatus at a pressure of 40 lbs. per square inch, and the lock was absolutely air-tight, not only at the beginning but during the whole time it was in use. When the tunnel had had to be driven through the bed of sand and gravel (it being impossible to alter the gradients so as to sink below it, and pumping from the surface being out of the question on account of the cost and the great danger to the surrounding property), the great difficulty had been to form some estimate of the amount of air which it would be necessary to provide to make up for the great loss escaping through the working face. At that time there had been no data upon which to proceed with reference to the quantity of air necessary. After some time it had been decided to erect a compressing plant, capable of compressing 1,500 cubic feet of free air per minute. The compressor which had been constructed for driving one tunnel, had two steam-cylinders, 18 inches diameter, working at a boiler pressure of 90 lbs. per square inch, and two air-cylinders 26 inches in diameter, coupled in tandem fashion to the steam-cylinders with 3-foot stroke. Those, when run at a rate of 50 revolutions per minute, gave an actual in-take of free air of 1,660 cubic feet per minute. In working the face by the method shown in the diagrams, during the first six weeks, when the material was of a very open character, it had been found necessary to run the engines at 50 revolutions per minute continuously; in fact, for six weeks the fly-wheel of the engine had never stopped. The anxiety with which the operation had been watched could be readily imagined. But about that time it had been suggested that grout should be inserted behind the poling boards. At first he had great difficulty in getting the men to adopt that method, as they were much prejudiced against it, but it was finally tried, and the effect of the grout behind the poling boards had been marvellous. It had been at once possible to reduce the speed of the compressors to between 30 and 40 revolutions per minute, and to double the progress at the face. He felt quite sure that, had it not been for the assistance given by the grouting apparatus in that way, the tunnel would not have been carried through so quickly, so successfully, or so cheaply as it

had been. The second tunnel had followed exactly on the same lines, the same size of compressor had been used, and the poling treated in the same way. The air-lock had been constructed on the lines followed in the first one, and the second tunnel, from the commencement to the finish, had passed through without the slightest hitch. A great many tunnels had been since constructed; but, as far as he could learn, the same lines had been followed; no great deviation from the mode of working having been adopted. Mr. Sewell

Mr. E. W. MOIR observed that the Author had stated that the circular form of lining was the best adapted to withstand the loads imposed upon a tunnel. No doubt the circular form of lining was best for a shield-driven tunnel, because every shield which had yet been used revolved more or less in its progress forward. In the St. Clair Tunnel the shields had revolved in the same direction, although they had been approaching one another, one 3 feet and the other 5 feet. At the Hudson Tunnel the shield in travelling 2,000 feet had revolved 5 feet. The Blackwall shield had revolved in two directions at different times. There was no accounting for the revolution, but in any other form than a circular one such a revolution would be very difficult to deal with. For that reason the circular form was no doubt the best. With regard to the shape for resisting pressure in the London clay, or in any other strata similar to it, a material that would stand more load as a re-action than the active load it would put upon the lining, it did not much matter what the shape was, for the lining spread out and filled any cavity, getting a reaction at the springing. Soft wood packings had been used by the Author between the ends of his segments; they practically became voussoirs of an arch on pinned ends, and they adapted themselves; if there was any space not absolutely filled by grout, the lining would immediately spread, a reaction was produced and greatly increased the strength. In soft river-mud and such material as was found in deltas, considerable bending moments were produced in the cast-iron lining, tension on the under-side of the roof, and tension at the springing on the back. The bending moments became a serious matter, and the tunnels were much strengthened by the addition of temporary ties across them if sufficient bending resistance was not imparted to the castings. Unfortunately, there did not seem to be any reliable method for calculating the strength of the lining, but there was no doubt that in soft muds the vertical axis ought to be longer than the horizontal one, and the same result might be achieved by partially filling the sides of a tunnel where space was not required with concrete. Inasmuch Mr. Moir.

Mr. Moir. as the cast iron of such undertakings cost from 30 to 40 per cent. of the total expenditure (in the St. Clair Tunnel he believed it was 33 per cent.), it was a great pity that some means could not be schemed for strengthening the lining, using temporarily a thinner casing, and ultimately reinforcing it by concrete or brickwork. Concrete might be used, and he believed was being used, with great advantage in the lining of the tunnels, and he did not see why, in the London clay and similar strata absolutely watertight, half or two-thirds of the lining should not be removed, and the lining so removed in short lengths replaced by concrete. An additional key could be inserted in the bottom of the lining, which could be drawn out by a union screw from above, or an hydraulic jack. He was sure a considerable saving would accrue in strata similar to London clay. Of course, in the case of gravel or water-bearing strata it could not be done with advantage. He noticed in the tunnel described, and he believed it was also the case in other tunnels though a shield had been used, the old scheme of getting outside and handling the muck and putting in timbering had been reverted to. That, he thought, was a source of delay and of considerable expense. In the case of the Blackwall Tunnel, and also in the case of the Hudson Tunnel, it would have been impossible to have gone outside the shield and done any mining. The river had broken in twice as it was at Blackwall, and then for days and weeks on end the ballast had been taken out through holes 7 inches by 3, it not being possible to pull back one of the shutters which protected the face. Even then, when the little shutters were opened to draw out the stuff, there was only a streak of fire and the escaping air, mixing the flints in such a hurly-burly as to cause sparks to fly from them. The shield ought to be provided with sufficient force behind it to make it do its own mining instead of getting outside and using it like a cheese-taster, paring off the ragged edges. The shield in New York had never been entered; it was all the time full of Hudson mud that was squeezed through the doors, 2 feet 6 inches by 2 feet, at a speed twelve times the rate of the advancing shield, caused by the great contraction in the area of the openings. A pressure of 1,000 tons had been applied to it, and it was so squeezed out that it could be picked up in great lumps and put on wagons without mining; in consequence only muck-fillers had been needed. It was the same thing at Blackwall. In the clay the face was chopped, and the shield driven at it, as much as 4,800 tons being applied behind it. It was stated by the Author that he preferred brick air-locks to those constructed

with iron cylinders built into a brick diaphragm. He could Mr. Moir. not agree with him for the following reasons. The Author's air-lock, as used at the Subway, was 12 feet long. It entailed a brickwork diaphragm, which was partly composed of blue brick, 16 feet 10 inches in thickness; that was only to withstand a pressure of 15 lbs. per square inch, and on an 11-foot 6-inch tunnel. The brick diaphragm at Blackwall, instead of being 16 feet 10 inches, was only 12 feet 6 inches, and it was in a tunnel 27 feet in diameter, and was designed to withstand a pressure of 35 lbs. to the square inch. Had the system of a brick air-lock been adopted a brick diaphragm 29 feet thick would have been required. The diaphragms at Blackwall were amply strong; they were, in fact, thicker than was needed, because it was necessary to have a certain bearing area for the brickwork on the flanges. He had calculated them on the basis that they concealed a dome within them, which was a very simple way of dealing with the matter. It had been stated by the Author that the opening in the diaphragm of the shield should be placed as low as possible, so that air space should always be left in the roof. No doubt that was an important matter—to leave a space in the roof where a man could always get his head, though he was up to his neck in water. On the 13th of April, 1895, while a tunnel was being driven under the River Yarra near Melbourne, some of the men had gone into the lock and seen Mr. Buchanan, the engineer in charge of the work, making efforts to induce them to open the lock-door. They had seen him waving a signal-lamp to open the door; but before they could do so the water had risen above the bull's-eye through which they were looking. The result had been that Mr. Buchanan and six miners were drowned. The shield which was being used was called in the reports the "Greathead shield"—as all such shields were now called; but generally in America they are called not the "Greathead" but the "Beach" shield. He mentioned the matter because he did not think the provision made in the shield used in the City and South London Tunnel, with a door of that kind, which was the same size as that of the Yarra shield, would be sufficient for safety. He had never found that the space between the tail-end of the shield and the cast-iron could be trusted to be air-tight. At Blackwall two men had been almost continually employed in pugging the place with soft clay. In addition to pugging with soft clay, which made the tail-end of the shield air-tight, and brought into effect the benefit of the hood in the shield, there had been a hanging screen a few hundred feet back from the face, which came half-way down

Mr. Moir. the tunnel. That converted the after part of the tunnel into a great diving bell. Should the water ever rise to its half diameter there was an emergency lock above the level of the bottom edge of the screen through which the men could get—a matter of great importance. On two occasions when the river had risen on them it had flooded the lower locks almost in an instant. The men had had to get in and out through the emergency lock, and indeed they could not have got on without it. Every tunnel of large diameter ought to be provided with a safety screen and an emergency lock as high up in the brick bulkhead as possible. In the Hudson and Blackwall Tunnels shield an attempt had been made to design a kind of submarine boat. Some of the most important features of it had been suggested by Sir Benjamin Baker, who had been consulted as to its design. In reference to compressed air, the Author had said that he had never had any difficulty with the men at the Subway. It had been Mr. Moir's unfortunate experience to see much disaster and death due to compressed air. When he had first gone to New York the men had been dying at the Hudson Tunnel at the rate of one man per month out of forty-five or fifty men employed—a death-rate of about 25 per cent. per annum. The shield had to be erected 2,000 feet out from the banks of the Hudson under a pressure of 35 lbs. per square inch, and that death-rate had increased to seven men in six months. An air-chamber had therefore been made in which the men could be treated homœopathically. It was erected on the top of the shaft, and when a man was overcome or completely paralysed, as he had seen them over and over again, completely unconscious and unable to walk, they were carried into the chamber, where the pure compressed air was raised to about a half or two-thirds of the pressure in which they had been working. The improvement was instantaneous. They were then let out at the rate of about 1 lb. per minute or even less; it took twenty-five or thirty minutes to bring them out, and even in severe cases the men were sent away rejoicing. The death-rate had been so far reduced in that way, that instead of having one man in fifty die per month there had only been two deaths in fifteen months out of one hundred and twenty men. No man ever suffered by going into compressed air unless his eustachian tubes were blocked, which was the mechanical effect of the pressure being on one side of the ear drum and not on the other, producing intense pain, and the man had to go out, unless he was relieved by swallowing or by holding the nose and blowing. He might go on with impunity for six months, and then one day he would come out in exactly

the same way, and find himself paralysed for life. He had known a very sad case in which a man worked six months, and was paralysed on his way home, falling between some railway wagons, where he lay all night. The medical lock had no effect upon him, and he remained paralysed to-day, and could not control his organs at all. It appeared to him that when a man went in under air pressure he was in the same condition as a furnace under forced draught. Suddenly three or four times the weight of oxygen was passed over his lung surface, or through his furnace; the system gradually assimilated itself to that increased oxygen, and more combustion went on. When he came out, however, and there was a sudden reduction in the amount of oxygen, the forced draught was shut off, and as it would be in the case of a furnace; there would be a production of carbonic oxide through insufficiency of oxygen to burn up the carbon in the coal. He thought that there was precisely the same effect in the case of compressed air. The carbon went on accumulating in the blood, and the man was actually poisoned by the effects of the carbonic acid or the carbonic oxide. That was proved from the fact that whenever air was of the slightest impurity—much less impure than in the room in which they were assembled, or in the Metropolitan Railway, or in many theatres—increased sickness was the consequence. The air had been analysed in the Blackwall Tunnel every week, and it had been found that if the percentage of carbonic acid was above one part in a thousand there resulted a great increase of sickness. Fortunately there had been no deaths, but there had been one case of paralysis which was cured immediately in the lock, and there had been one or two cases of vertigo, one of which was more or less permanent, though he had heard that the man was now recovering. The great necessity was to have plenty of air. The quantity which was found to produce the required results was 2,000 cubic feet per man per hour. With that quantity a pressure of 35 lbs. per square inch could be maintained without difficulty. No doubt the purity of the air was the great secret of the health of the men. Mr. Moir.

Mr. J. WOLFE BARRY, C.B., Vice-President, had read the Paper with great interest. The system of burrowing or dipping so deeply under ground was one which necessitated the employment of means such as had been pointed out by the Author; but he thought from his own experience of London locomotion that the important thing to be considered at the present time was the question of cost, and he hoped that some particulars would be given of the cost of the cast-iron tunnels, so that it might be compared with the cost of the larger tunnels such as had been Mr. Barry.

Mr. Barry. employed for those very important means of locomotion, the Metropolitan and the Metropolitan District Railways. It had been truly said by the Author that there had been very little increase in the means of railway locomotion in London since those railways were put to work. The real reason for that was that it was now found extremely difficult to make Metropolitan railways pay interest on their cost. The competition on the surface, the improved paving of the streets, combined with the improved road traction by tramways, road-cars, and means of that kind, which would take a passenger up and put him down exactly where he wanted to be placed, rendered it extremely difficult to make Metropolitan railways or any Metropolitan means of communication pay, unless they could be made cheaply. To his mind, therefore, the crucial point for the future of the interesting works described in the Paper was what they cost as a means of locomotion in London. As far as the use of compressed air was concerned, it was perfectly true that it must be of the greatest possible utility in water-bearing strata; but a question lying at the root of the matter was, whether it was advantageous or not to go to great depths, with cast-iron tunnels and compressed air, and in doing so to incur the cost of a very expensive lining. He had recently, in conjunction with his friend Mr. Forman, been engaged in making a railway through the very heart of Glasgow; and he thought it might be of interest to state the cost of the railway, which had been made like the Metropolitan Railway, close to the streets, with large stations and convenient platforms, with few steps and consequently with very easy access. He could give the contract prices through the densest part of Glasgow, along Trongate and Argyle Street, which might be compared almost with the Strand, and certainly with Oxford Street and Regent Street, for traffic. The three contracts worked out thus: In the Bridgeton contract, the contract cost, including everything except station buildings and permanent way, amounted to £94 per lineal yard; the Trongate contract £141; and the Stobcross contract to £90. The contracts had not been adjusted, and therefore he could not say that that would be the ultimate cost; but he knew of nothing that had arisen which would seriously disturb those figures. He had also abstracted some figures from the Trongate contract, which embraced the railway through the most crowded part of the city, with a covered way which was constructed of brickwork arching, but mainly with expensive wrought-iron girders and jack arches. He had taken out the cost, including all the street restoration, the underpinning of property, sewers and drains,

Mr. Barry.

and the laying of the permanent way—in fact, everything but stations and station buildings. In one district the cost was £65 per lineal yard, in another £73, in another £64, in another £113, and in another £115. It would be of interest to compare the figures with the cost of cast-iron tunnels, including the same items of cost as he had included, and not merely the cost per running yard of the tunnels themselves, as it must be obvious that, *cæteris paribus*, the nearer to the street a railway was, the more convenient it must be. It was not an advantage to go down to a great depth into the soil, and the only reason for doing it was the avoidance of cost. He did not think any question of property would disturb the comparisons which he had proposed, because the railways in question went down the middle of wide streets, and very little property had been bought. As far as the working of the underground railways was concerned, it would be clear to every one that there was no reason why deep lines should have the monopoly of electricity. If electricity was the best motive power he saw no reason why it should not be applied to the ordinary underground railways of the country; and he hoped to see it so applied. The French were so applying themselves to the problem. He had seen drawings in Paris of a very powerful locomotive worked by electricity for conveying the ordinary traffic of the railway running from Paris to Mantes. An experimental engine had been running nearly a month, and a larger one was now being built.[1] The engine was not at present strictly an electric engine, except that the wheels were turned round by an electric current. The generator which produced the electric current was on a travelling platform, and the current was produced by an ordinary steam-locomotive boiler, supplying steam to a Parsons engine mounted on the same frame and these engines actuated the dynamos. It seemed at first to be a rather roundabout way of applying electricity, but he had been told by the engineers in France that they were satisfied there was economy in it, and that better results were produced by those steam-engines in the way of economy and fuel, and that the advantage of using electric motors for the revolution of the wheels of the locomotive was very conspicuous in the subdivision of power, the avoidance of reciprocating parts, and matters of that kind. He believed that in two or three months they would hear of one of those engines being at work on the Rouen line. They of course would not

[1] Minutes of Proceedings Inst. C.E., vol. cxiii. p. 481.

Mr. Barry. assist in the ventilation difficulty of underground lines being in themselves steam-engines working also electrically. He thought that every one must feel interested in the subject of working under compressed air, which had so many aspects in regard to the question of coping with water-bearing stratifications with comparative facility. Although compressed air did not work with the facility that some persons imagined, it enabled them under proper conditions to do many works which had never been before dreamed of.

Deacon. Mr. G. F. DEACON wished to refer to the tunnel carrying the Vyrnwy Aqueduct (76 miles in length) under the tidal River Mersey. The construction of that tunnel had been a well-marked step in the history of shield work. The undertaking had been singular and remarkable in three respects—firstly, owing to Parliamentary exigencies and a decision of the Board of Trade, the tunnel had been placed where no engineer would have chosen to drive it; secondly, it was the first tunnel ever constructed by means of a shield through entirely water-bearing strata beneath a river tidal or otherwise; thirdly, the difficulties had been at first so great that about nine-tenths of the time occupied in the work only sufficed to complete the shafts and about one-fifth of the length of the tunnel, the remaining four-fifths having been constructed in about one-tenth of the whole period. When it had been found that a tunnel was inevitable, he had at first intended to construct it through the boulder clay formation at a depth of about 80 feet below the level of ordinary spring tides. Without actually requiring the use of a shield, he had stated in the specification for this work his desire that a shield of the kind used in the Tower Subway by the late Mr. Peter Barlow, F.R.S., and subsequently, with certain modifications, by Mr. Greathead for the City and South London Railway, should be employed. He had not believed that in this formation artificial air-pressure need be maintained for the driving, and, having regard to the depth, he had thought it better to dispense with it. The contract had been let in April, 1888. The contractors, however, had not used a shield, but had continued—while tunnelling through boulder clay—the air-pressure employed in sinking the Cheshire shaft. In October, 1889, when the work had reached about 57 feet from the centre of that shaft, the tunnel had been flooded, and in October, 1889, the original contractors had ceased to act. At this period eighteen months had already elapsed, and within three months a contract was let to other contractors, who had elected, and had been permitted, to drive the tunnel at a higher level and above the boulder clay. It had been known from borings which had been

previously made that the strata at this level would be entirely Mr. Deaco water-bearing, that they would be loose, of constantly varying descriptions, and that they would differ largely even at single sections in the depth of the tunnel. At the point of commencement on the Lancashire shore the invert of this tunnel was 52 feet below high water of ordinary spring tides. The shield used by the contractors was precisely as described by Mr. Peter Barlow, and since used by Mr. Greathead in the London clay of the City and South London tunnel and elsewhere. The first difficulties met with had arisen from the circumstance that the ground had been disturbed by the shaft-sinking operations of the former contract. Cast-iron tunnel segments weighing 4 cwts. each, sawn timber and many other materials drawn down from above had been taken out, and when at length the shield had reached the natural strata they had been found, as expected, to vary—even in the small diameter of 10 feet—from silt, through running sand and small gravel, to rough ballast and occasional veins of clay. It had soon become apparent that the shield was too weak, and after many serious difficulties had occurred the lower part of the cutting-edge had buckled inwards for about a quarter of the circumference to a maximum extent of 15 inches or 16 inches, and at the same time a longitudinal crack had been found near the bottom extending from the tail nearly to the diaphragm. At this juncture the second contractors had objected to continue the work under their contract.

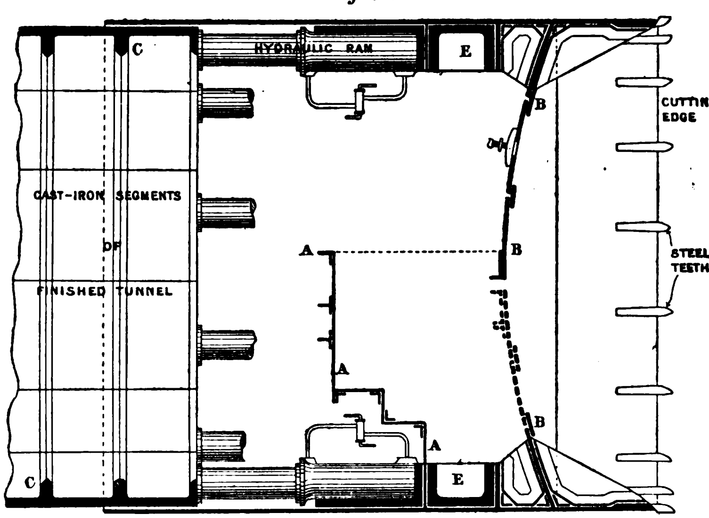
After such a succession of difficulties and in face of the fact that no tunnel had hitherto been completed under similar circumstances, there had been little hope of obtaining contractors to carry out the work for a fixed sum of reasonable amount. Moreover, it had been urged that success was impossible. On the other hand, his observation had led him to believe that the work was not only possible but certain of accomplishment under conditions which might still be ensured. He had previously proposed to the Corporation of Liverpool to carry out the work without entering into an ordinary contract, and nothing more had remained but to do this, or to abandon the work performed, and incur the delay of a further application to Parliament for a new route not only for the river crossing, but for much of the already completed aqueduct. The opposition to his views had been considerable, and there was serious risk of the tunnel being abandoned. In a report dated the 13th of October, 1891, he had expressed his belief thus:—"With a shield properly designed to pass through the different classes of material met with the work can be accomplished by next summer." And he concluded this report as follows:—"The frequent examin-

Mr. Deacon. ations of the subaqueous workings, which I have myself made, have only served to confirm my belief in the practicability of the undertaking without immoderate cost. At the same time it should be remembered that I did not seek this method of constructing the crossing. It has been forced, as I venture to think, uselessly upon the Corporation, by the Board of Trade, and it has seriously delayed the completion of the great undertaking of which it forms a small but essential part. Nothing, it appears to me, remains but to push on the work with due deliberation, unslackened energy and full confidence in the result." Wiser counsels had at length prevailed, and it had been resolved to continue the work. He had stated that in his belief the tunnel could be completed "by next summer." It had been in fact completed by the following March.

A new agreement had been entered into with the contractors to continue the work at prime cost under his (Mr. Deacon's) directions as to the methods to be employed, with Mr. Arthur H. Cochrane to take charge of the men and materials; Mr. A. W. Brightmore (who from the beginning had acted ably as Resident Engineer) continuing to act in that capacity. It would have been a long and difficult matter to replace the damaged shield in such a position, and it had therefore been decided to strengthen and repair it, with no certainty, but with a strong hope, that it would survive the future ordeal. Moreover, the ground could not at any other place have been less favourable for the work than that in which the shield then stood. In about seven weeks the operation of strengthening and repairing the shield had been successfully performed. An important addition suggested by Sir Benjamin Baker had been at the same time made. He referred to the bird fountain device shown in *Fig. 31*, which was a section of the shield as used in the construction of four-fifths of the length of the tunnel. When the diaphragm B of an ordinary shield was partially open for access to the face and a "blow" took place, there was nothing to check the momentum and tumultuous energy of the entering water until it had risen in the finished tunnel C above the level of the opening in the diaphragm. A second diaphragm had therefore been introduced at A, a few feet back from the main diaphragm, and having its horizontal sill above the level of any opening—such as that shown by dotted lines—to be used in the main diaphragm. It was clear that—with this arrangement—if the pressure in the tunnel balanced or exceeded the pressure of the water without the tunnel, no serious flooding could occur; while if the second diaphragm at A were absent and the equilibrium was once lost, flooding might continue to a serious

extent. The device differed entirely from anything shown in the drawings accompanying the Paper; it was in no sense a high-pressure air-lock. With the dotted portion of the main diaphragm removed, a man might stand between the two diaphragms, and even outside the outer diaphragm, with comparative safety, and could always rapidly make his way to the air-lock; and while doing so, the inner diaphragm prevented that calamitous rush of water which had produced disaster in so many cases. A movable lid was provided, as shown by the dotted line at A B. In the case of one blow which had subsequently occurred, it had proved to be practicable to replace this lid Mr. Deacon

Fig. 31.



Scale, ¼ inch to 1 foot.

and thus further to steady the rush. In another case, however, this could not be done, and a large quantity of water, sand, and silt had been discharged into the tunnel, but happily without loss of life such as might have occurred if it had not been for the modifying effect of this device. At the same time the shield was greatly strengthened by means of a ring of cast-iron girders E and in certain other ways. The steel teeth were also added. The work had been recommenced, slowly at first, but with increased speed as experience had been gained. At the end of six weeks, however, the longitudinal crack already referred to had become worse, and another crack had worked from it circumferentially across the

Deacon. bottom of the shield. The resistance to progress of the shield had been increasing, and this was found to be due to the fact that the front edge of this fracture had turned down and was ploughing the strata as it advanced. It was impossible to avoid a stoppage. The ground was as bad as it could be; but notwithstanding this and a water-pressure of 54 feet at high tide, a piece of the annular shield was successfully cut out, $6\frac{1}{2}$ feet long and 9 feet wide circumferentially, and replaced with new plates bolted to the cast-iron ring girder, and not connected longitudinally or elsewhere, so that they simply overlapped, were supported by and were dragged over the finished cast-iron work. The portion cut away could not be removed, but was left behind when the shield advanced. The operation had only occupied twelve days, and after this repair no serious difficulty with the shield had occurred. During its progress heavy trunks of oak timber lying prostrate were met with. These greatly retarded the work, and had to be cut away at the rate of 18 inches at a time. The maximum speed attained had been 19 yards a week, and the Cheshire shaft had been reached on the 22nd March, 1892, some months earlier than he had ventured to predict. The whole length, 618 feet, driven with the improved shield, had occupied, including all stoppages, four and a half months. The tunnel was in every sense a complete success. It remained so dry that the hydraulic pumps, worked by pressure of Vyrnwy water—which are automatically started by the rise of water in the sump below the Lancashire shaft—were very rarely brought into use, and then chiefly owing to condensation of moisture on the ironwork.[1] In all successful work of this kind a large proportion of the credit must be attributed to those constantly on the spot, and he could not speak too highly of the care and attention devoted to the matter by Mr. Brightmore and Mr. Arthur Cochrane.[2]

Greathead. Mr. Greathead in reply said, in reference to the expedient used in the Vyrnwy Aqueduct tunnel for preventing sudden "blows" or inrushes of water and materials through the face of the shield, that the same device had been used in the shield made for the Woolwich tunnel, *Fig. 18.* A second diaphragm, placed in rear of the face of the shield and extended from the bottom up to a level

[1] The hydraulic pumps are further referred to in Minutes of Proceedings Inst. C.E., vol. cxv. p. 251.

[2] More complete information on this subject and concerning the principles to be observed in shield tunnelling is given in a Paper by G. F. Deacon, published in the Report of the British Association for the Advancement of Science, 1892, p. 532.

above that of the top of the opening in the face, made it impossible for the air to escape so long as its pressure did not exceed that of the water, or for the water to enter the tunnel so long as its pressure did not exceed that of the air acting upon the horizontal surface of the water between the face and the diaphragm. The air-lock shown in *Fig. 18* might obviously be placed anywhere in the tunnel; in this case, air-locks had been provided for use in both places, that in the tunnel consisting of two iron diaphragms on wheels, capable of being moved forward from time to time. The account given by Mr. Deacon referred to two tunnels, one of which was started in 1888 without a shield. This tunnel, although compressed air had been used, had been driven in eighteen months, only some 57 feet from one of the shafts, when it was flooded and subsequently abandoned. Soon afterwards, he (Mr. Greathead) had been consulted by Messrs. Cochrane & Sons, who had offered to complete this tunnel. Having regard to the great depth at which the tunnel was proposed to be placed, viz., at one end 113 feet below high water, and to the fact that it was not in impervious strata, he had advised that the offer should be withdrawn, and that it would be much easier to construct a tunnel by shield and compressed air at about half the depth, or some 50 feet below high-water level through the alluvial strata disclosed by the borings. At this time the tunnels of the City and South London Railway had been successfully driven through the most difficult water-bearing gravels, without pumping, as described in the Paper. The second tunnel had been subsequently started by Messrs. Cochrane & Sons, and, as having been responsible for its being placed at the higher level, he would point out that the whole of the difficulties connected with its construction had arisen from the fact that the shield was crippled in some way at the start, probably by contact with the cast-iron segments referred to by Mr. Deacon. The shield was not, as stated by Mr. Deacon, precisely the same as those used in the City and South London Railway tunnels, and described in the Paper. The cutting-edge was made to project about 3 feet in advance of the face of the shield, and it was this projecting cylinder that had become deformed. As stated in the Paper, any change of shape at the cutting-edge would inevitably lead to trouble, and this was not the only tunnel where such trouble had occurred. As soon as this defect was discovered and corrected and the shield strengthened, the work went forward quite satisfactorily. But for this mishap there was no doubt the tunnel would have been driven through in three or four months from its start.

Greathead. In regard to Mr. Barry's remark as to the cost of work at Glasgow, he would ask whether it would be within the limits of practical engineering to suggest that that which had been done in Glasgow should be attempted in London. He had frequently been in Glasgow, and had seen rows of piles driven down along both kerbs, and he thought that was a mode of construction that could hardly be contemplated in London. Mr. Barry had given the prices of some of the tunnels there, and had made certain deductions from them for the absence of underpinning. He did not think it would be possible to carry out any construction going below the foundations of houses in London without underpinning them. But taking the prices that Mr. Barry had given for tunnels in Glasgow, he could only say that the prices of the two tunnels in the City and South London Railway were about half his minimum. The lowest cost per yard was stated by Mr. Barry to be £90; but the two tunnels of the South London Railway were constructed for £45 per yard, including everything except stations.

Mr. Barry. Mr. BARRY said he had not deducted the underpinning, but included it.

Greathead. Mr. GREATHEAD understood it was included in some cases; but he did not gather that there was any underpinning in the tunnels given as costing £90 per yard.

Mr. Barry. Mr. BARRY said that the second prices he had given excluded the stations only, everything else was included.

Greathead. Mr. GREATHEAD said in the case of iron tunnels there was no street restoration, underpinning of property, interference with sewers and drains, driving of sheet piling in the streets, or surface work of any kind, and the cost per lineal yard of double tunnel, which included the permanent way, was the equivalent, therefore, of the figures given by Mr. Barry, except that it should be borne in mind that the cost of materials, of carting and of labour was higher in London than in Glasgow, and that railways along the Strand, Oxford Street and the City streets would not be constructed "down the middle of wide streets," as Mr. Barry had stated the Glasgow lines were. It would, therefore, have made a more satisfactory comparison if Mr. Barry had given the cost of his underground railway work in London, as, for instance, the tunnel under Cannon Street.

It was not quite obvious that the nearer to the street a railway was, the more convenient it must be. If the railway could be placed quite near, with its platforms not more than 15 feet below the surface, it might be considered preferable to placing it at a depth so great as to involve the use of lifts; but certainly stations

at 50 feet or 60 feet down with good lift accommodation would be preferable to stations at half that depth without lifts. Then the opposition to railways near the surface, under the streets as well as under houses, would be great on account of apprehended noise and vibration in working, in addition to inconvenience from construction. The avoidance of cost was not, therefore, as Mr. Barry stated, the only reason for going down deep into the soil. Mr. Greathe

In reference to the shape of tunnels, he maintained his opinion that for an iron tunnel the circular section was preferable to any other under most conditions. Local requirements might necessitate a departure from that section, as in the case of a tunnel recently constructed by him in Dublin, or in soft silt and similar strata it might be advisable to adopt an oval section, and in such cases there would not be the difficulty Mr. Moir apprehended in carrying out that section with a shield. The fact that the shield in its progress had a tendency to rotate upon its axis was not a reason for adopting the circular form, but, on the contrary, it would rather be a reason, though not in itself a sufficient one, for a departure from that form, because rotation of the shield would then be prevented by the iron lining. There was no mystery about the cause of the rotation. It was undoubtedly due to the action of the hydraulic presses or screws (it had occurred in the Tower Subway shield), and resulted from their combined thrust being out of parallelism with the axis of the shield. He had suggested as a remedy that the presses or some of them should be so attached to the shield that their direction could be adjusted slightly to counteract any tendency of the shield to rotate. The taking out of iron and substituting concrete for it in the lining of the tunnel had often been considered; but he was satisfied that, with the present price of iron at any rate, that would certainly not be an economical method of proceeding in London, and it would lead to considerable loss of time and some risk, in most cases, of injury to property. There were localities, no doubt, where concrete would be more economical than iron, but it would probably be found best in such cases to build the tunnel of concrete in the shape of moulded segments or blocks, thoroughly set and hardened before use. Concrete in this form, unlike "green" concrete, would be capable at once of resisting pressure and of excluding water. The unfortunate catastrophe in Melbourne had been referred to by Mr. Moir. He (Mr. Greathead) had not been consulted about that tunnel, but he heard that the contractors for that work had sent to some merchants in London for a shield, and

Greathead. that a shield had been obtained made from the designs of the City and South London shields. It had been sent out and set to work. He hardly thought he should be held responsible for what might happen under those conditions. A shield was not a thing to be ordered as a plough, for every tunnel had to be treated in a special manner. With regard to the hydraulic erector referred to in the Paper, all the drawings, not only of the erector, but of the shield and other parts of the tunnel at Woolwich, designed between 1874 and 1876, could be seen.

There was no suggestion in the Paper that brick air-locks should be used under all conditions and sizes of tunnels; and the question was not so much one of cost as of the health of the men, who, both on the City and South London Railway and on the Waterloo and City Railway, had a decided preference for the brick over the iron air-locks. The possibility of taking a lock forward through another lock was, in driving long tunnels, also a considerable convenience. Similarly, it was not suggested, as Mr. Moir assumed, that in a large tunnel the shield should be regarded as a substitute for safety screens in the tunnel. In small tunnels it was not possible to introduce hanging screens; but, in any tunnel large enough to admit of it, at least one screen should be provided and carefully maintained air-tight, and, whereever practicable, the road in rear of the screen should at one point be elevated to a level above that of the lower edge of the screen by inclines in both directions, and carried over a watertight bank in the invert. To avoid the inconvenience of the gradients, it was quite feasible to take the road through a gate in the bank, closing fairly watertight, and kept closed by springs or otherwise, except at the time of the passage of trucks, &c. Even when a tunnel was being driven on an ascending gradient, and where a simple hanging screen might be useless, this arrangement would secure the whole of the air-locks in the bulkhead against the possibility of being submerged. It was suggested by Mr. Moir that the tunnels in the London clay should be driven in the same way as the Hudson Tunnel had been, and that, in tunnelling through gravel under streets, the same mode of attack should be adopted as in the Blackwall Tunnel. Under all conditions the shield should, no doubt, be made to do as much of the mining as possible; but in tunnelling, as in other matters, different cases required different treatment, and London clay could not be dealt with precisely in the same way as soft silt, nor was it feasible to let down the surface of the streets in the way that the bed of a river might be. It was of the first importance, in driving through

the loose water-bearing strata on the City and South London Railway, to avoid the slightest disturbance overhead, and that condition had been fully attained by the method employed. Mr. Greath

No special castings were used in the City and South London tunnels in driving round curves, the difference in length between the inner and outer circumferences being made up by filling in the joints; but on the sharper curves of the Waterloo and City Railway special castings had been introduced. The adjustable cutters of the shield, described in the Paper, had been found to act admirably, when properly regulated, in tunnelling round curves. As the tunnel under the Seine at Clichy had been referred to, he might perhaps be allowed to state that the shield for that work had been constructed in this country from his (Mr. Greathead's) designs, and that his compressed-air grouting apparatus had also been employed there. The cost of this tunnel, as given by Mr. Fitzmaurice, viz., £29 per foot, appeared to be very great for a diameter of only 7 feet 7 inches. The contract price quoted from Mr. Parson's report as that of the Waterloo and City Railway tunnels, viz., £32 per foot of double tunnel, was for the tunnels constructed under compressed air through water-bearing gravel. The price for the tunnels in clay was about £24 per foot of double tunnel.

The use of shields in clay had been referred to by Mr. Binnie, who seemed to think that they were not of much use there except as supports to avoid the use of timber. He (Mr. Greathead) took a very different view. He was quite satisfied that the London tunnels could not have been constructed without shields, even in clay. There was the important question of speed. Unless the tunnels could be constructed at great speed, it would be necessary to have temporary shafts in the streets; and it was known what the London County Council would say to a proposition to place temporary shafts along Oxford Street, for example. He did not think that a tunnel could be constructed with perfect safety without a shield. When passing through clay, a shield was an assurance against other things that might be met with. The shield also led to a considerable reduction of labour. The introduction of the wedges in front of the shield, which threw upon the hydraulic presses some of the work of excavation, had led to a very material acceleration of the work and a corresponding reduction in cost. In fact, in the City and South London tunnels the introduction of those wedges had almost doubled the speed in constructing the first tunnels. That was a very important matter, in view of the present price of labour. In stating that the City

r. Greathead. and South London and the Waterloo and City tunnels were as easily constructed as would be a tunnel under Primrose Hill, Mr. Binnie had overlooked the fact that in both those cases compressed air had to be employed within a few yards of the Thames to keep back the water from the river. He need not follow Mr. Binnie through his remarks on the Brunel patent, which was described in the Paper, except to say that, in common with all engineers, he had the greatest admiration for Brunel, and that if he had said in the Paper that the Thames Tunnel had acted as a warning to engineers, he had done no more than state a fact. As to the Cochrane patent (also described in the Paper), it was really a patent for air-lock arrangements, and for certain arrangements for removing excavated material; it was not a patent for tunnelling through loose water-bearing strata under compressed air. The drawings produced by Mr. Binnie showed a section of a tunnel in clay, and the end of the tunnel was perfectly open. No doubt Lord Dundonald contemplated the use of compressed air in tunnelling, but he had not devised any means by which it could be used in loose or open water-bearing strata.

Surprise had been expressed by Mr. Crawford Barlow that reference had not been made at all to the work of the late Mr. Peter Barlow. It was impossible within the limits of a single Paper to describe fully all that had been done, much less, every patent that had been taken out, but as a former pupil of Mr. Peter Barlow, he had desired to give due prominence to his work, and the Paper contained a description of the Tower Subway and of Mr. Barlow's Omnibus Subway scheme. He had not thought it necessary to refer to the Southwark Subway scheme, in which he had been associated with Mr. Barlow. It was an extension of the Tower Subway idea and embraced a small tube 8 feet in diameter and 1,200 yards long, with a lift for twenty passengers at each end, and carriages propelled by a wire rope and two stationary engines. After the failure of this arrangement at the Tower Subway, it was found impossible to proceed with the undertaking. Until Mr. Crawford Barlow stated that a patent had been taken out by his uncle in 1868, he (Mr. Greathead) had not known of it, and that was no doubt due to the fact that Mr. Barlow attached so little importance to the subject that he did not proceed beyond the preliminary stage with his application for a patent. The shield used at the Tower Subway was described in the Paper and was not as represented in either of the figures presented by Mr. Crawford Barlow.

As to the question of Mr. Lewis whether the grouting had been

tested, the fact that at the stations about 2,000 feet in length of the tunnels had been taken out was referred to in the Paper, and the perfect condition of the grouting behind the iron lining described. Within half-an-hour of its injection the grouting was generally as hard as the clay, and in a short time it became much harder, and it was therefore capable of taking the pressure transmitted by the clay. The cases of damage to property on the railway had been occasioned by the construction of the brick-lined tunnels, and were not due to any enlarged iron tunnels. As regards pumping, the success of the system of tunnelling described was due to the avoidance of that source of expense and danger. Mr. Greathead.

Correspondence.

Mr. JAMES ARMER stated, with reference to the tunnelling in connection with the metropolitan sewerage system, under the river Yarra in Melbourne, that, a former section of the work having been abandoned on account of the difficulties in driving through the silt formation, a shield had been made and sent from England early in 1894. It was 11 feet in diameter, and was in other respects identical to those employed on the City and South London Railway. The length adopted for the rings of the tunnel lining had been 2 feet 9 inches. During August, 1894, the rate of advance by this shield had been 11 feet 8 inches per shift of eight hours, an increase of 18 inches in the rate being anticipated with the addition of segment-lifting arrangements. The progress made in the same time by a shield constructed in the colony and working under similar conditions had been 2 feet 9 inches. The work under the Yarra was of a more dangerous character than that described in the Paper; but the accident in April, 1895, would appear to have been in no way attributable to the shield. Mr. Armer.

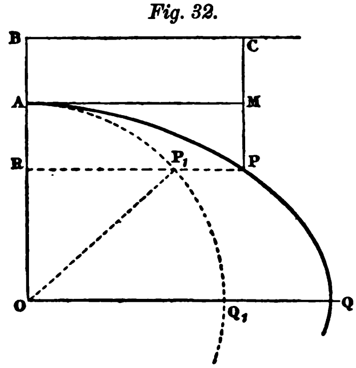
Mr. C. J. BELLAMY observed that the "hydrostatic arch" was well known to be the form suitable for sustaining the pressure of a perfect fluid, provided that its weight might be neglected, as being very small compared with the pressure of the fluid. This arch was not a closed curve, but a succession of loops. If, however, the weight of the arch itself was taken into account the curve became considerably modified, and there was a particular relation between the weight of the arch and the pressure of the fluid, for which the curve became a circle, as would be shown. In *Fig. 32* A P Q was a cross-section of the semi-arch at right angles to its length, and B C the surface of the fluid. The vertical forces Mr. Bellamy.

Bellamy. which kept the portion of the arch A P in equilibrium were the weight of the fluid A B C P, the weight of the portion of arch A P, and the vertical component of the thrust at P. Hence, equating the resultant of these forces to zero—

$$\int_0^x w\,(a + y)\,d\,x + v\,s - t\,\frac{d\,y}{d\,s} = 0 \quad . \quad . \quad . \quad (1)$$

where A B $= a$, A M $= x$, M P $= y$, A P $= s$, $w =$ weight per cubic unit of fluid, $v =$ weight per square unit of arch surface, $t =$ linear thrust at any point P per unit length of arch, and T $=$ linear thrust at A the highest point of the arch, where the curve was horizontal. The horizontal forces acting on A P were the thrust at A, the

Fig. 32.



horizontal pressure of the fluid on the vertical plane M P, and the horizontal component of the thrust at P. Hence

$$\mathrm{T} - \int_0^y w\,(a + y)\,d\,y - t\,\frac{d\,x}{d\,s} = 0 \quad . \quad . \quad . \quad (2)$$

Differentiating equations (1) and (2) with respect to s—

$$w\,(a + y)\,\frac{d\,x}{d\,s} + v - \frac{d\,t}{d\,s} \cdot \frac{d\,y}{d\,s} - t\,\frac{d^2\,y}{d\,s^2} = 0 \quad . \quad . \quad (3)$$

$$-\,w\,(a + y)\,\frac{d\,y}{d\,s} - \frac{d\,t}{d\,s} \cdot \frac{d\,x}{d\,s} - t\,\frac{d^2\,x}{d\,s^2} = 0 \quad . \quad . \quad (4)$$

Multiplying (3) by $\frac{d\,y}{d\,s}$ and (4) by $\frac{d\,x}{d\,s}$ and adding them together the resulting equation became—

$$v\,\frac{d\,y}{d\,s} - \frac{d\,t}{d\,s} = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Mr. Bellamy.

therefore $\dfrac{dt}{dy} = v,$

and $$t = \mathrm{T} + v\,y \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Inserting this value of t in equation (2) and performing the integration in that equation, there resulted—

$$\frac{dx}{ds} = \frac{\mathrm{T} - \frac{w}{2}(a+y)^2 + \frac{w}{2}a^2}{\mathrm{T} + v\,y} \quad . \quad . \quad . \quad (7)$$

If b be the value of y, when the curve became vertical as at Q, at which point $\dfrac{dx}{ds} = 0$,

$$\mathrm{T} = \frac{w}{2}\left\{(a+b)^2 - a^2\right\} \quad . \quad . \quad . \quad . \quad (8)$$

Substituting this value of T in equation (7)—

$$\frac{dx}{ds} = \frac{(a+b)^2 - (a+y)^2}{(a+b)^2 - a^2 + \frac{2v}{w}y} \quad . \quad . \quad . \quad . \quad (9)$$

If now a particular value be given to v, viz., $\dfrac{wb}{2}$, equation (9) reduced to—

$$\frac{dx}{ds} = \frac{b-y}{b} \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

If in *Fig. 32* the horizontal line Q O be drawn, and with O as centre the circle A $\mathrm{P_1}$ $\mathrm{Q_1}$ be described with radius O A, and the horizontal line P $\mathrm{P_1}$ R drawn, then at the point $\mathrm{P_1}$ on the circle

$$\frac{dx}{ds} = \cos \mathrm{A\,O\,P_1} = \frac{\mathrm{O\,R}}{\mathrm{O\,P_1}} = \frac{b-y}{b};$$

therefore the curve of the arch A P Q coincided with the circle A $\mathrm{P_1}$ $\mathrm{Q_1}$. This particular value which had been given to v, viz., $\dfrac{wb}{2}$, implied that the weight of any portion of the circular arch as A $\mathrm{P_1}$ was equal to the weight of fluid corresponding to the sectorial area A O $\mathrm{P_1}$, so that if the curve comprised the entire circle the weight of the cylinder was equal to that of the fluid it displaced; and with this condition the circular cross-section was a curve of equilibrium; and there was no bending stress on the cylinder, whatever be the depth of its immersion.

Mr. Brightmore. Mr. A. W. BRIGHTMORE wished to add a few details in connection with the Vyrnwy Aqueduct tunnel under the River Mersey. The tunnel shafts were built of cast iron, and were 800 feet apart from centre to centre. The depths of the shafts to the invert-level on the Cheshire and Lancashire shores of the river were 46 feet and 52 feet respectively. The external diameter of the tunnel was 10 feet, and that of the shafts 10 feet 9 inches, the latter being widened at the bottom to 15 feet. The minimum height of the river-bed above the tunnel was 20 feet, and the invert-level was about 50 feet below high water. The shafts were built of flanged cast-iron rings, 4 feet deep, varying in thickness between 1 inch and $1\frac{1}{16}$ inch, down to the widened part, which was built of smaller segments. The tunnel was built in rings, in each of which were ten segments, 3 feet by 1 foot 6 inches and $1\frac{1}{16}$ inch thick, weighing 4 cwt. each, and a key-segment, 1 foot by 1 foot 6 inches, weighing 1 cwt. The shafts had been sunk by loading the cylinders and excavating with a grab in the ordinary way, and nearly four-fifths of the tunnel had been driven by means of an improved shield; ten hydraulic rams, 7 inches in diameter, and working at a pressure of 1,000 lbs. to 2,000 lbs. per square inch, being used to force it forward. As the shield had usually a tendency to droop at the cutting-edge, it had been seldom necessary to employ the upper rams—a circumstance, no doubt, due to the greater resistance at the bottom of the shield. When there was no unusual obstruction, the friction in the shield amounted to about 4 cwt. per square foot, and sometimes to somewhat less.

The pressure of air in the tunnel was usually between 12 lbs. and 15 lbs. per square inch above the atmosphere, often about two-thirds the hydrostatic pressure of the water outside. As a rule it had been necessary to pump into the tunnel 500 cubic feet of air per minute (measured at atmospheric pressure), and in exceptional cases more than double that amount. Two methods of working had been employed. When, owing to the fairly uniform permeability of the strata, the air escaped evenly through the face and kept it dry, except quite at the bottom, the men, while standing in front of the diaphragm, excavated for about 18 inches beyond the cutting-edge; the pressure being then turned on to the rams, the shield advanced into the space so prepared. When the air escaped unevenly, the face, or a portion of it, was wet, and the men excavated standing in the pocket between the two diaphragms, the pressure being kept on the rams, so that the shield crept forward as each spadeful of material was removed, until it had advanced 18 inches. The time taken to advance the

shield this distance and get out the excavation was practically the same with both methods. The next ring of segments was then fixed for the excavation to be resumed as before. It was worthy of remark that, after the improved shield had been put to work, the time taken for the excavation and advance of the shield was fairly constant, at the rate of about one hour and a half for each ring, unless there was some unusual obstruction. On the other hand, the fixing of a ring of segments took at first four hours; but when the men were well drilled to the work, this rate was greatly increased, and before the completion of the tunnel it had been found possible to fix a ring in one hour and a half. The leakage of water into the tunnel during the driving had varied between 30,000 gallons and 40,000 gallons per day. Mr. Brightmore.

Mr. E. G. Carey remarked that the rapid development of the system of tunnelling described in this Paper had led to the design of special plant, for the manufacture of the cast-iron segments of the lining. Those for the Glasgow District Subway were almost identical with those for the City and South London Railway, and were moulded in specially designed machines consisting of a 4-inch hydraulic ram working both the pattern and the box. A pair of side levers, actuated by a second hydraulic ram 2 inches in diameter and of 11 inches stroke, held the swing-head in position, the latter consisting of a cast-iron girder, with a hard wood ramming-block bolted to its lower side. Four guides, 4½ inches in diameter, were secured to the cast-iron bed-plate to direct the actions of the ram which was counterbalanced. The empty moulds were conveyed beneath the machine on bogies and were transferred to it by the outline plate which was swung over. The ram then brought the pattern into place, sand being fed in from a hopper above, and the swing-head was then raised, and the ram caused to bring a final pressure to bear on the sand. The ram was then lowered, withdrawing the pattern and the swing-head being thrown back, the mould was turned over on to the bogie beneath by the outline plate. A hand-screw withdrew the pattern ends from the mould. The hydraulic pressure was 1,500 lbs. per square inch. Each of these machines produced 1½ ring per hour (9 segments per ring). The total quantity in the Glasgow District Subway was 20,000 tons. Mr. Carey.

The Blackwall Tunnel segments had been machine-moulded, their size prohibiting hydraulic moulding. The moulding-machine consisted essentially of a main framing of cast-iron, carrying both pattern and moulding box, and capable of turning completely over on side hinges. The pattern flanges were operated by four hand-wheels, 24 inches in diameter, to enable the mould to leave the

Mr. Carey. pattern, which was of mahogany, brass bound at the edges. The pattern with flanges in position, and mould-box being in place, sand was shovelled in and rammed, the lid was then clamped on and the main framing thrown completely over. The flanges were then withdrawn and the mould received the hand-moulded top portion. This machine would make between thirty and thirty-three segments in the working day of nine and a half hours, the maximum attained in this time being thirty-six segments. The segments of the Edinburgh Mound Tunnels, and the Glasgow Central Railway sewers, were hand-moulded, the quantities required not warranting the construction of special plant. Special milling plant had been designed for machining the ends and sides of the segments. Two types had been adopted, viz., the work stationary and the tool travelling, and *vice versa*. The milling heads, whether travelling or not, were essentially the same in each type and were furnished with cutting tools about 3 inches apart on the circumference. More than 50 miles of milling of 10 inches wide planing was thus performed. The patent moulding and milling plant had been constructed from the designs of Mr. Stephen Alley, Glasgow, at the works of the British Hydraulic Foundry Company Limited, Whiteinch, Glasgow.

Mr. Fox. Mr. Francis Fox, of Westminster, had had considerable experience with the Greathead shield and grouting machine, and desired to bear his testimony to the great value of these appliances, which together formed one of the greatest improvements that had been introduced into the art of tunnelling during the last thirty or forty years. They had, to a great extent, deprived subaqueous or submarine tunnels of the risk formerly attending their execution, and had also, under many circumstances, much reduced their cost. Such tunnels could now be driven safely and rapidly through silt, gravel and sand, previously impassable at any reasonable cost. It might be true that the idea of a shield was not a new one; and the late Sir Charles Fox, M. Inst. C.E., had employed cement grout under hydrostatic pressure for the repair of cracks in brickwork, as early as 1865. The system of blowing in the grout by compressed air, introduced by the Author, was, however, a great improvement upon the hydrostatic process; and, having employed it upon several occasions, and under varying circumstances, he had formed the highest opinion of its efficiency, and commended it to the attention, not only of engineers, but of architects, for the grouting of masonry or brickwork showing cracks due to settlement, or other causes. For the repair of cathedral or church towers, or tall chimneys, he considered that it would prove

of the greatest value, the cost of its efficient application to ensure the safety of the structure being probably not one-fiftieth part of the expense which would be incurred in rebuilding. He would not attempt to express an opinion as to the probable originator of a shield, for which several claimants had been put forward; but he considered that the credit of introducing, practically applying, and working out to a satisfactory completion the system under review was undoubtedly due to the Author, and that his name would be inseparably connected with this most important addition to the resources of civil engineers engaged in the construction of tunnels. Mr. Fox.

Mr. Halpin. Mr. DRUITT HALPIN observed that a useful Table of costs of construction of various underground railways was given in the Zeitschrift des Vereines deutscher Ingenieure of the 26th October, 1895.

Mr. Hawkshaw. Mr. J. C. HAWKSHAW considered that the process of tunnelling by means of a shield and compressed air, which had been so successfully used and so well described by the Author, was, and always would be, of great value in driving tunnels through water-bearing strata at no great depth below the surface of the water which determined its pressure. But the limiting depth at which the shield process could be used was soon reached; probably 80 feet would be a maximum depth. The cylinders of Londonderry Bridge had been sunk by compressed air under a water-pressure of 80 feet, but five men had lost their lives owing to the severity of the work under such a pressure. That the process described in the Paper could be used only in tunnels at a comparatively shallow depth must be sufficiently obvious. It had been inferred that the Severn Tunnel could have been, or could now be, more cheaply constructed by using a shield with compressed air, and that similarly the Channel Tunnel and the Irish Tunnel could be more cheaply constructed by the same means. Compressed air could not be used in connection with a shield to keep back water at the tunnel faces in any one of the three cases mentioned. The least depth of the rail-level below high water, in the Severn Tunnel, was 80 feet close in shore; and it increased to 160 feet below the shoots and to 200 feet at the drainage heading. In the English Channel there was a depth of 120 feet of water, and the tunnel itself would have to be at a much lower level, probably between 250 feet and 300 feet below the surface of the water. In any tunnel to Ireland the depth would be greater still, as there was a sounding of 500 feet in the channel between the two countries. In the cases of the three tunnels mentioned, therefore, the process

Mr. Hawkshaw. adopted with such success on the City and South London Railway could be of no avail. If a second Severn Tunnel were made, all the water penetrating into the working would have to be pumped, and so it would be if tunnels were made beneath the channel between England and France, or between England and Ireland. The practicability of making such tunnels depended on whether the whole of the water entering the workings could be dealt with by pumping. If it could not there was no known process by which such tunnels could be made.

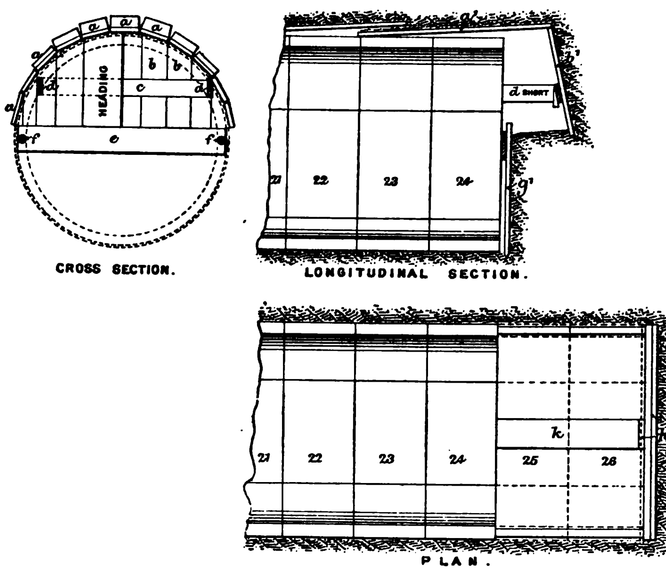
Mr. Hay. Mr. DAVID HAY stated, with reference to the alignment of the tunnels described in the Paper, that, in order to determine their exact positions, an accurate survey had been made, showing the main roads to be followed and the buildings fronting upon them. This survey having been laid down to a scale of 10 feet to an inch, the centre lines of the tunnels had been marked, and points in the straight portions measured off from prominent buildings. These points had been established in the road, either by driving thin steel wedges between the setts where the road was paved, or by iron pins 12 inches long where it was macadamised, a centre-punch mark being made in either case. The lines had then been measured to the nearest curb, so that the marks might be easily found or reinstated if destroyed. The base lines thus fixed had been extended, and where they intersected each other the angle had been read off with a theodolite, the lengths between the points of intersection being carefully measured. In consequence of the heavy vehicular traffic all along the route of the railway during the day, it had been found possible to do this work only at night or early on Sunday mornings. In the former case a tissue-paper screen, held in front of an electric lamp driven from a primary battery, had been found most useful for sighting. In consequence of the shafts having been at some distance from the tunnels, the lines fixed on the surface could not be directly transferred to the tunnel. It had therefore been necessary to ascertain the angle between the line of the cross-passage and the line of tunnel. After the shaft had been sunk, the line of the cross-passage had been set out on the surface and the point of intersection, with its angle, fixed and read in the usual way. Two plumb wires had then been sighted into line in the shaft, to which the cross-passage had been driven the requisite length. The wires had been again sighted, and the distance, from the intersection to one of them, accurately measured on the surface. The theodolite had then been taken below and set up in the line of wires at a distance from them corresponding with that measured on the

surface, and the angle read off, thus determining the line of tunnel to be driven. This operation had been repeated two or three times at each station until a sufficient length of tunnel had been driven to admit of a reliable base line being established. The most convenient method of establishing points had been found by filing nicks in staples driven into hard-wood wedges fixed between the cast-iron rings at the top of the tunnel. When sighting a plummet line in the staple, the tissue-paper screen had been placed behind it; and when the atmosphere in the tunnel was clear extreme accuracy had been possible, the smallest variation of the line being easily detected. A clear sight, however, could seldom be obtained with the theodolite for more than 250 feet or 300 feet, on account of the smoke from the candles, &c.; recourse had therefore to be had to a long steel piano-wire $\frac{1}{32}$-inch thick to produce the straight lines. This wire had been sometimes used for lengths up to 700 feet and had been stretched along the roof of the tunnel out of the way of traffic. By the use of plummets with fine steel points and thumbscrews for adjusting the wire great accuracy had been obtained, and after the first base line had been established it had never been found necessary to use the theodolite until a curve was reached. The line staples had been driven about every fifty rings, but never close to the shield, as there was a danger of the lining moving slightly. Daily checkings of the portion of the lining fixed had been made with a shorter wire, one end being attached to the third staple from the face, and the other end fastened to the shield. It had then been adjusted by the other two staples, a light plummet line being hung upon it opposite the last ring, and measurements being taken to check the position. A 7-inch theodolite had been used by Troughton and Simms. No special rings of cast-iron lining had been used for the curves; consequently iron packings had to be placed between the rings to make the joints radiate from the centre point of the curve. When approaching a curve the side of shield on the outside was made to lead a distance corresponding to the iron packing to be inserted, and at the same time the cutting edge of shield was freed on the inside of curve. This latter was a very important point and must be insisted upon, otherwise the men would neglect it, as it gave them a good deal more trouble. Mr. Hay.

Mr. W. A. P. Tait observed that the tendency appeared, from Table II of the Appendix, to be in the direction of an increase in the internal diameter of subways for electric or cable railways. It would be useful if the Author would not only state the cost of the lines of 10 feet 2 inches and 12 feet 6 inches internal diameter, Mr. Tait.

Mr. Tait. but the probable cost in similar circumstances of lines large enough to take the ordinary railway rolling-stock and satisfy Board of Trade requirements. It appeared a short-sighted policy, even though there might be a small saving, to construct subways of such small diameter as to cause the equivalent of a break of gauge. The permanent way was of the ordinary gauge, but there could not be reciprocal running powers. He understood that the air of the District Railway contained between twenty-two and thirty parts in 10,000 of carbonic acid, a somewhat larger ratio than found in an

Figs. 33.



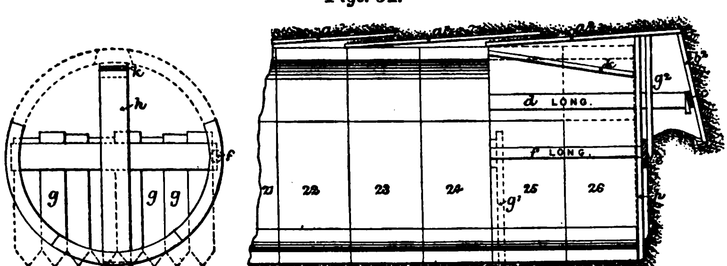
Scale, ¼ inch to 1 foot.

average theatre. Analyses of the air in the tunnels worked by the electric engine would be interesting.

Regarding the driving of the tunnels, he had had charge during construction of two of the small tunnels under the streets of Glasgow referred to by the Author. One of 4 feet internal diameter had been driven through wet sand, gravel and ballast, without a shield, and had proceeded at the rate of 1½ yard daily at each face. The progress of the other with a shield had been less satisfactory. It had been usual to take out, at one time, excavation for two complete rings of cast-iron, each made up of six segments, representing an advance of 3 feet. Eleven poling boards, *aa*, *Figs. 33*, supported at their

leading ends by *bb*, had been used to support the roof until the Mr. Tait.
two rings of the lining were finally erected. The other ends of the polings had been supported on the last completed length. The crown polings rose 3 inches in their length forward to allow for subsidence, and still permit the placing of the poling for the next length beneath. In order to "get in the top" for the rings Nos. 25 and 26, for example, the miner first removed a leg *b*, under a crown poling a^1 and drove a heading, shown in the section, the full length, about 4 feet, of the new poling board, a^2, and immediately propped it with the old leg, b_2, *Figs. 33* and *34*, and so on, widening the heading out to either side until all the new polings, a_2, were inserted and supported by legs, b_2. Great care had been taken to cover each of the polings before they were inserted with a layer of well-tempered clay. This had occupied the time of two miners, who in the limited space could only work

Figs. 34.



CROSS SECTION. LONGITUDINAL SECTION.

Scale, ¼ inch to 1 foot.

alternately, and a labourer about four hours. The legs, b_2, were then secured by a waling *c*, *Figs. 34*, held by two rances, *d d*, butting against the flange of the ring last erected. Next a waling *e* (held in same way) was set up so as to be somewhat more than 3 feet from the last ring, in order to let in two rings of 18 inches each. A series of piles, g_2 and *g*, *Figs. 34*, were set up and worked home as a little excavation was taken out. Little by little the dumpling had been removed, until at last one half of the length had been bottomed. Some difficulty had occasionally arisen at this stage, if the air-pressure was not maintained, and great care was necessary in taking out the last of the muck. In such a case the bottom plates had been laid in water. This second stage had occupied about three hours. After the bottom segment had been inserted, the trouble was much reduced, and the work became more easy. Before the second segment from the bottom could be

Mr. Tait. inserted, one of the rances, *f*, had to be removed, but it had been temporarily replaced by the soldier and stretcher, *h* and *k*, *Figs. 33* and *34*, but as soon as the second segment of ring 26 had been inserted, the waling, *e*, had been dwanged from the flange of that segment. The subsequent grouting had been as described by the Author. While all the polings used were allowed to remain, the rest of the timber was used again and again, the long and short pairs of rances *d* and *f* being used alternately.

A curious paradox in connection with the driving of tunnels in compressed air under the River Clyde had been noticed, viz., that a lower pressure often sufficed to keep the tunnel dry at high than at low water. This had been possibly due to consolidation of the silt by the increased superincumbent pressure. In view of the fact that excavation at a working face, unless supported, did not stand vertical, it occurred to him some years ago that in order to effect greater progress with a shield, the roof should be prolonged slightly so as to take the natural slope. This would, to some extent, obviate the present practice of working in advance of the shield; but care would have to be taken to prevent the shield from turning about its axis, a circumstance which occasionally happened.

Greathead. Mr. GREATHEAD, in reply to the correspondence, said that in fixing 80 feet as the maximum depth under water for tunnelling by shield and compressed air, Mr. Hawkshaw was not far wrong if he meant that the pressure of the air was to be, as usually in shaft sinking, such as to completely balance the head of water; but there were occasions when this was by no means necessary, and where compressed air could be used in tunnelling at much greater depths than 80 feet with great effect as regarded safety and economy. There could be no doubt that in cases where much water was encountered at great depths, whether compressed air were used or not, it would often be economical to put in cast-iron lining to avoid the permanent cost of pumping. The reduced quantity of excavation would generally in such cases balance the extra cost of iron over brickwork. It was stated by Mr. Carey that the cast-iron segments for the Glasgow District Subway were almost identical with those of the City and South London Railway. The design of the latter had, however, been departed from in the former in one respect which it was worth while to notice. The longitudinal joints, instead of being made with flat faces of the whole depth of the flanges, Fig. 16, Plate 2, had been made like the vertical joints in the City and South London tunnels, with a chipping edge or fillet along the outer edge of the flange. Where

rigidity was required to prevent deformation and to secure the maximum efficiency of the iron this form of longitudinal joint, with a soft-wood packing between the flanges, appeared to him to be an unfortunate modification, because the bearing-surface of segment against segment was practically reduced to the width of the chipping edge with the result that there was very little resistance to outward movement, away from the centre, at any of these joints. Mr. Greathead

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26 November, 1895.

SIR BENJAMIN BAKER, K.C.M.G., President,
in the Chair.

The discussion of the Paper on "The City and South London Railway" occupied the evening.

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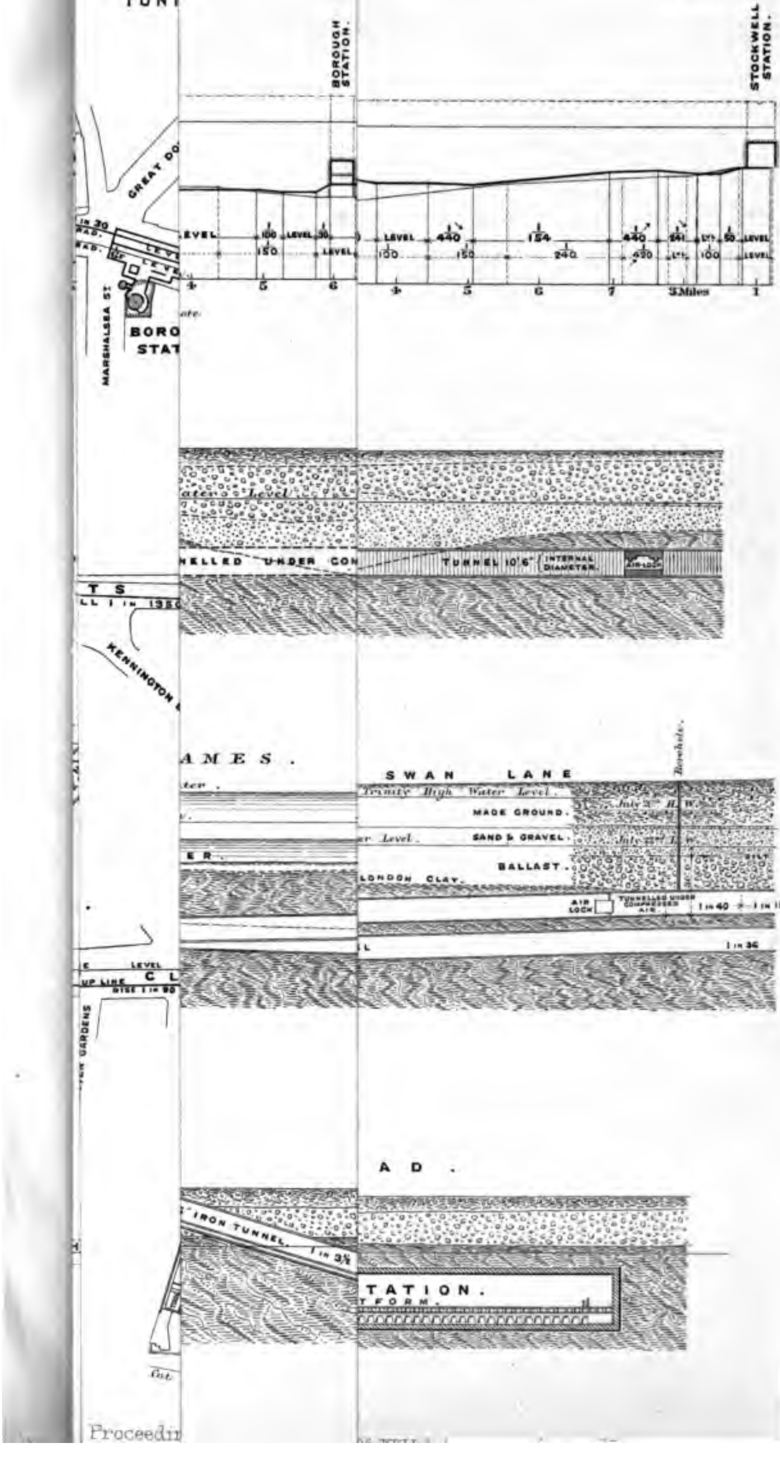
PLATE 1.



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